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COMPARATIVE LIMNOLOGY OF HARP AND JERRY LAKES - ADJACENT COTTAGED AND UNCOTTAGED LAKES ON SOUTHERN ONTARIO'S PRECAMBRIAN SHIELD

Ministry of the Environment
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SOUTHERN ONTARIO'S PRECAMBRIAN SHIELD

by
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SUMMARY AND CONCLUSIONS

1. The limnology of two adjacent lakes near Huntsville, Ontario was studied during 1973 and 1974. The lakes are similar in morphometry and drainage basin characteristics, but Harp Lake is heavily developed with cottages while Jerry Lake is uncottaged.

The major objectives of the studies were: (a) to develop phosphorus budgets for both lakes and solve for the cottage input component by utilizing relationships between total phosphorus loading, retention and sedimentation as measured for both cottaged and uncottaged lakes; and (b) to relate differences in the measured P budgets to differences in fundamental limnological characteristics.

Important mineral and nutrient constituents in inflowing and outflowing streams, euphotic zones and bottom waters of the two lakes were studied. Hydrologic and phosphorus budgets for the two lakes were developed. As well, the gross sedimentation rates of total suspended solids, organic matter, nitrogen and phosphorus were determined and related to dissolved oxygen deficits both during the summer stagnation period and under the winter ice cover. The seasonal distribution of plankton biomass and its composition were determined.

2. The waters of both lakes and inflowing streams were generally very similar in concentrations of mineral constituents and compared with those of some of the most dilute lakes of the world. Jerry Lake and its inflowing streams were more highly coloured and higher in iron content than Harp Lake and its inflows. Some evidence was found for "freezing out" of major constituents in the lakes during early winter ice formation.

3. Dissolved oxygen deficits, both under winter ice and during the summer stagnation period were more severe in Jerry Lake where rates of sedimentation of total solids, organic matter, nitrogen and phosphorus were higher. Hypolimnetic dissolved oxygen depletion rates in both lakes were twice as high during summer as winter depletion rates owing to ice-free period rates of organic matter sedimentation averaging 2-3 times higher than during the winter ice covered period.

4. Nitrate-nitrogen in both lakes was a much more important form of inorganic nitrogen than was ammonia-nitrogen, although euphotic zone concentrations of total inorganic nitrogen during most of the ice-free period were low (10-30 μg N/l). Total phosphorus concentrations in the Jerry Lake inflow and the Harp Lake inflow, averaged about 50 μg P/l and 30 μg P/l, respectively during the ice-free period. Euphotic zone concentrations averaging 18-20 μg P/l were found in Jerry Lake in contrast to Harp Lake's 12-13 μg P/l. A slight trend to higher bottom water concentrations of total P in Jerry Lake was noted during the latter stages of summer stagnation and corresponded with an increase in iron to 3.2 mg/l and depletion of dissolved oxygen. No increases in P or Fe were noted in the bottom waters of Harp Lake where dissolved oxygen depletion was less severe.

5. Phosphorus mass balance equations were developed and simplified to:

$$J_E + J_{PR} + J_A = O_T + S_{net}$$

for Harp Lake, and

$$J_E + J_{PR} = O_T + S_{net}$$

for Jerry Lake, where

J_E = total P supplied from natural land drainage
J_{PR} = total P supplied from the atmosphere
J_A = total P supplied from cottaged lots
O_T = total P output through the outflowing stream
S_{net} = net sedimentation of P within the lakes.

All components of the Jerry Lake equation were determined. J_A (and consequently S_{net}) was unknown from measurements on Harp Lake; but, S_{gross} (gross sedimentation of P measured in traps suspended near the lake bottom) was measured for both lakes. A ratio of S_{gross}-to-S_{net} was calculated for Jerry Lake and applied to Harp Lake enabling S_{net} to be determined which in turn resulted in a calculated J_A to Harp Lake of 20.3 kg P/yr or 0.28 kg P/cottage·yr.

The studies on Harp and Jerry Lakes suggest therefore, that for tile fields constructed in about 2m of the Wendigo and Monteagle loam-sand complexes which are prevalent throughout southern Ontario's Precambrian Shield, an export value of 0.3 kg P/cottage·yr may be realistic, assuming that the ability of tile field soils to retain phosphorus does not decrease with increasing age of the tile field system.

It is important to point out that the source of the apparent P input (20.3 kg/yr) associated with cottages on Harp Lake has not been determined. Some may derive from seepage from septic tank-tile beds and some from clearing of vegetation and other lakeshore based activities associated with development and use of cottaged property. Clearly, a better understanding is needed of P dynamics in soils of the Precambrian Shield before artificial loading of P to lakes from associated cottaged development can be predicted with confidence.

6. The seasonal distribution of the phytoplankton biomass and the species composition in Jerry Lake seem typical of other oligotrophic, humic waters in hard rock areas of the north temperate climate. Despite lower total P concentrations within Harp Lake, there are signs of eutrophication in the lake. High mid-summer biomass of chroococcalean blue-green algae were present in Harp Lake (also indicated by chlorophyll *a* measurements) yet did not materialize in Jerry Lake and therefore suggest that some of the annual nutrient input from the cottaged areas gained access to the lake during the mid-summer period which was also when most of the cottages were inhabited. Heavy rainfall (6 cm) during the last few days of July may have facilitated the transfer of nutrients from the cottage areas.

Another important difference in phytoplankton composition between Harp and Jerry Lakes relates to the occurrence in relatively high densities of the diatom *Tabellaria fenestrata* in Harp Lake and its virtual absence from Jerry Lake's phytoplankton. Historical data from European lakes suggest that this may be a sign of incipient eutrophication of Harp Lake. Species composition of the zooplankton also points to a more mesotrophic status of Harp Lake than the oligotrophic (and humic) Jerry Lake.

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Mrs. E. Carney and Mr. R. Strus analyzed phytoplankton and zooplankton samples.

Many of the data were summarized and tabulated by Miss D. Crocker and Miss. C. Babuska.

Most of the chemical analysis were performed by staff of the Water Quality Section, Laboratory Services Branch.

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INTRODUCTION

Cottage development and recreational use of inland lakes in Ontario is continuing to expand with approximately 10,000 new cottages being constructed annually (Schenk 1971; Department of Tourism and Information 1971), and with relatively heavy recreational use now extending into the winter months in many areas of the Province.

Changes in the nutrient enrichment of recreational lakes are especially difficult to assess in cottaged lakes of the Precambrian Shield. Yet a naturally shallow, sandy soil mantle usually overlies impervious, igneous bedrock of these areas and may offer little retention of nutrients in seepage from cottage waste disposal systems (Ellis and Childs 1973; Bouma et al. 1972; Wall and Webber 1970). The Ontario Ministry of the Environment has undertaken several research and monitoring programmes designed, in part, to document the trophic status of recreational lakes in the Province and to date, limnological data have been collected on more than 300 lakes. These data will have important historical significance in assessing any long-term changes in trophic state of these lakes.

The nutrient loading and budgeting concepts as pioneered by Vollenweider (1968, 1969 and 1975) have found useful practical application in the assessment of the significance of nutrient loading to lakes from a variety of land use types (Dillon and Rigler 1974; Jonasson et al. 1974; Welch et al. 1975; and others reviewed by Vollenweider and Dillon (1975). Of particular significance to management of lakeshore of recreational lakes is the approach taken by Dillon and Rigler (1975) to calculate the capacity of a lake for cottage development based upon a prediction of in-lake trophic reponse to phosphorus loading to the lake and upon estimates of phosphorus inputs from the drainage basin including inputs from local cottage waste disposal systems. To be reliable and useful, predictive models such as that of Dillon and Rigler (1975) must employ accurate data on phosphorus loading to lakes from cottage septic tank-tile field sewage treatment systems. In most studies to date, information on nutrient loss to lakes from cottage septic tank-tile bed systems has been based on per capita-year estimates (calculated from the numbers of dwellings and rates of occupancy) assuming a certain percentage retention of P by lakeshore

soils. No successful attempts have been made to measure, either directly or indirectly the magnitude and significance of nutrient input to a lake from cottaged lakeshore. Also apparently lacking, have been detailed comparative limnological studies of small, morphometrically similar Precambrian Shield lakes with the exception of the on-going Experimental Lakes Area study (Johnson and Vallentyne 1971).

Complying with the original objectives of the Ministry's Recreational Lakes Programme to document water quality in recreational lakes, an uncottaged lake (Jerry Lake) near Huntsville was studied in 1972 to determine water quality in a lake unaffected by nutrient inputs associated with cottage development. It became clear early in the study, that because of possible differences in rates of supply of nutrients from the drainage basins of cottaged and uncottaged lakes, simple comparisons of indices of enrichment such as lake concentrations of constituents, for example, may not yield the information needed to adequately assess the effects of lakeshore cottage development. Therefore, and in recognition of the role of phosphorus as a limiting nutrient in Precambrian lakes (Schindler et al. 1973; Michalski and Conroy 1973, Michalski et al. 1973), the studies on Jerry Lake were expanded in 1973 to include discharge measurements on the inflowing and outflowing streams and calculations of a P budget. Concurrent work on a nearby similar but cottaged lake (Harp Lake) was also begun in 1973 for comparative purposes and measurements of atmospheric loading of P were included (Nicholls and Cox 1976).

Although not appearing to suffer from excessive nutrient inputs and in fact, showing very appealing water quality, Harp Lake presented a challenge to demonstrate whether subtle differences between the two lakes existed which could be linked to cottage development of the lakeshore.

The major objectives of the studies on Harp and Jerry Lakes were therefore, (a) to solve for the cottage input component of a P mass balance equation developed for the cottaged lake by utilizing relationships between total P loading, total P retention and total P sedimentation as measured for both the cottaged and uncottaged lakes; and (b) to relate differences in measured P budgets to differences in fundamental limnological characteristics.

Considerable emphasis was given to comparison of the plankton composition and density in Harp and Jerry Lakes since historical documentation of the eutrophication process in other lakes has provided evidence that increased

production and biomass of total plankton in eutrophying lakes has been often associated with changes in taxonomic composition (Davis 1968; Bonomi et. al. 1968; Government of Northern Ireland 1968; Int. Wat. Protec. Comm. for Lake Constance 1968; Lund 1969; Morgan 1970; Szymanski-Bucarey 1974; McNaught et. al. 1975; Hickel 1975). Furthermore, taxonomic studies of phytoplankton in lakes influenced by similar geologic and climatic factors but differing in trophic status suggest that the composition of the plankton may be an important indicator of lake "physiology" (Findenegg 1965; Schindler et. al. 1973 and 1974; Gorham et. al. 1974). In some cases the magnitude of differences between lakes in plankton composition and biomass greatly exceed the small differences measured in water chemistry and other environmental factors (Willen 1969; Cheng and Tyler 1973; Happey-Wood 1975), and can therefore be a very sensitive and useful indicator of the trophic state of a lake.

Studies identical to those carried out on Harp and Jerry Lakes, were also completed during the same time period on two very eutrophic Precambrian Shield lakes (MacLean and Riley Lakes) to provide similar information relative to nutrient and plankton dynamics over a wider range of lake trophic state. Results from these studies will be reported separately.

STUDY AREA

Harp Lake and Jerry Lake are situated in Chaffey and Sinclair Townships, respectively, in the District Municipality of Muskoka, approximately 9 km northeast of the town of Huntsville, Ontario (Fig. 1). The distance between the lakes is approximately 0.8 km and they are located within the Muskoka River watershed which is part of the Georgian Bay Terminal Drainage Basin. The immediate catchment of each lake is small but Jerry Lake receives runoff from a land area of 7.3 km^2 - almost twice the size of Harp Lake's catchment (4.0 km^2); otherwise the lakes have very similar morphometric features (Fig. 1 and 2).

Harp and Jerry Lakes lie at elevations of 326m and 328m above Mean Sea Level (MSL), respectively, while bedrock relief on the northern boundary of their catchment attains an elevation of 412m above MSL. The soil depth over bedrock is generally less than 0.5m. There is much exposed bedrock within the drainage basin of the lakes and is especially

prevalent along the north shoreline of Harp Lake and along the east shoreline of Jerry Lake. The bedrock is a slightly granitized and banded biotite-migmatite which is highly metamorphosed and of Precambrian age (Ontario Department of Mines, 1948). Extensive deposits of mainly fine sands can be found along the northeast shoreline of Jerry Lake with more bouldery glacial till material present along the west shore of Jerry Lake and the south shoreline of Harp Lake. The dominant soils of the area belong to the Wendigo and Monteagle loam - sand complexes developed over bedrock (Canada Department of Agriculture and the Ontario agricultural College, 1964).

Jerry Lake receives drainage from the west through a small intermittent stream while the major inflow comes from the northeast through two streams which drain beaver ponds in their upper reaches and merge before entering the lake (Fig. 1). The major inflow to Harp Lake enters from the west (Fig. 1). Three other small streams flow only intermittently, especially the southerly and westerly streams which were dry except during the spring snow melt period. In contrast to Jerry Lake, there was no beaver habitation on the inflowing stream to Harp Lake but the head waters of the main inflow originated from springs in a lowland area of cedar and hemlock about 1km north-west of the lake. None of the streams monitored for flow and nutrient regimes (see below) were in close proximity to human habitation and it is believed that stream water analyses were indicative of natural land drainage (or lake outflow) only, with no direct influence from cottaged areas. The outflowing streams exit from the southeast and south ends of Harp and Jerry Lakes, respectively, and merge downstream to enter Penninsula Lake approximately 1.5 km below the confluence.

The land surrounding Jerry Lake is privately owned with access to the lake by a private road extending north approximately 1.3 km from highway No.35 and 60. The lake has received limited use, with hunting, fishing and camping pursuits generally restricted to the land owners. A boathouse constructed at the south end of the lake is the only man-made structure on the lake although use is sometimes made of a cabin located about 0.5 km south of the lake on the access road. Very little evidence remains of the limited logging operations carried out many years ago within Jerry Lake's drainage basin.

There are seventy-three vacation homes or cottages on the shoreline of Harp Lake, which are served by a road circling the lake. Cottage development began about 1955 and by the time of the study in 1973, only a few vacant

lots existed, mainly at the western end of the lake. Approximately one-half of the dwellings have been constructed within the past ten years and most utilize septic tank-tile bed systems for sewage waste treatment. A few of the dwellings have been winterized and are inhabited year round.

The fisheries of the lakes appear to be somewhat different; however, the differences may be in part related to artificial plantings, with Harp Lake presently being managed by the provincial Ministry of Natural Resources as a lake trout/smallmouth bass (Salvelinus namaycush/Micropterus dolomieui) fishery. Both lakes have in the past been planted with speckled trout (Salvelinus fontinalis). Jerry Lake also supports lake trout but yellow perch (Perca flavescens), catfish (Ictalurus sp.) and several Cyprinids are common in Jerry Lake yet absent or of minor importance in Harp Lake (W. Ellerington, Ministry of Natural Resources, personal communication). Recent sightings of smelt (Osmerus mordax) in the Jerry Lake outflow during the spawning season (R. Hutcheson, personal communication) might indicate that this species has extended its range northward into Harp and Jerry Lakes from Peninsula Lake where it is known to exist.

Littoral zone areas and volumes are very similar relative to total lake areas and volumes (Table 1). As well, the littoral zones of both lakes were sparsely populated by similar macrophyte associations (Isoetes sp., Nuphar sp., Nymphaea sp., Pontederia cordata, Fontinalis sp., and Potamogeton natans).

Based on long-term average data provided by Environment Canada, the climate of the Huntsville area is characterized by an average of 189 frost free days per year with a mean maximum diel temperature of 25.7C during the warmest month and a mean minimum diel temperature of -15.3C during the coldest month. Annual precipitation approximates 63.2 cm as rainfall and 282 cm as snowfall (total as water equivalent = 91.7 cm). Lakes in the area are generally ice-covered for a five month period from December until May.

METHODS

At the deep water locations of both lakes, samples for phytoplankton, chlorophyll, nutrient and mineral chemical analyses were collected during the ice-free period as composites through the euphotic zone by allowing weighted sample bottles to fill as they were lowered and raised through a depth of twice the Secchi disc visibility. Under winter ice cover, surface, 5m and 10m samples were collected with a Van Dorn bottle. Additional samples for chemical analysis were regularly collected at 1m above bottom and often at 2m and 3m above bottom with a Van Dorn bottle. Dissolved oxygen was determined on samples collected at 5m intervals with a Van Dorn bottle when

Table 1: Comparison of the [1]littoral zone areas and volumes of Harp and Jerry Lakes

	Littoral Zone Area		Littoral Zone Volume	
	$m^2 \times 10^5$	Percentage of Total Lake Area	$m^3 \times 10^6$	Percentage of Total Lake Volume
Harp Lake	3.01	40	1.29	12
Jerry Lake	1.72	31	0.68	9

[1]Assuming a littoral zone bound by the lake surface and lake bottom to a depth of twice the average Secchi disc visibility.

the azide modification of the Winkler method was used (further modified for field use by the use of dropper reagent bottles and 60 ml ground glass stoppered sample bottles) or at 1m or 2m intervals if a meter (E.I.L. model 15A or Y.S.I. model 54) was used. Temperatures were usually recorded from the same instruments.

Personnel of the Ministry's Hydrologic Data Section installed staff gauges in the inflowing and outflowing streams of both lakes and periodically calibrated the gauges with flow metering apparatus. Local residents were employed to record the staff gauge readings and to supplement Ministry collection of water samples at the gauge sites throughout the year. Owing to difficulty of access to Jerry Lake streams during winter and spring, the frequency of gauge reading and sample collection was about once per week; however, measurements were made every two or three days through these periods on Harp Lake where access was not so difficult or dangerous. Such arrangements often led to time delays in sample analyses, so some samples were stabilized to pH 2 with sulphuric acid after collection and analyzed up to two weeks later for total phosphorus only. Analyses for all other constituents were carried out on samples which were collected by our own staff and delivered to the Toronto laboratory within one to two days of collection.

During the principal year of the study in 1973, no collections or analyses of rainwater were made. However, a large combination rainfall gauge and collector was installed on a rocky shoal on Harp Lake approximately 50m from the southwest shoreline in 1974. Analyses of precipitation (and dry fallout) samples collected during 1974 yielded data on nutrient loading from the atmosphere during both ice-free and winter periods (Nicholls and Cox 1976). These data were applied to the precipitation data collected at nearby Huntsville during the period of the Harp and Jerry Lakes study, assuming little difference in fallout of pollen etc., and nutrient content of precipitation between the lakes and from year to year.

Sedimentation traps, similar in function to those used by Bloesch (1974) but in the form of quadruplicate, attached, 500 ml wide-mouth polyethylene bottles, were filled with distilled water and 20 ml of Lugol's iodine solution was pipetted into the bottom of two of the four bottles. Traps were suspended at 1m above bottom and 20m above bottom in both lakes for intervals of from one to two weeks during periods of thermal stratification and under winter ice cover. The preserved portions of the trapped sediment were retained for microscopic examination while the contents of the

unpreserved portions of the trap were analyzed for total suspended solids, loss on ignition, phosphorus and nitrogen.

Most chemical methods (Ontario Ministry of the Environment, 1974) were colourimetric and based on "Standard Methods" (American Public Health Association. Procedures for the enumeration of phytoplankton followed American Public Health Association (1971) utilizing a Sedgwick-Rafter counting chamber and a magnification of 200X after prior concentration by settling in Lugol's solution. Difficulties with taxonomy or enumeration were generally resolved by using a wet mount at higher power or an inverted microscope. Biomass was expressed as cell volume by an approximate comparison of the cells to geometric objects of known volume. Phytoplankton taxonomy generallyfollowed Huber-Pestalozzi (1938, 1941, 1942, 1968).

RESULTS AND DISCUSSION

I. PHYSICAL-CHEMICAL-HYDROLOGICAL

Temperature and Dissolved Oxygen

Both Harp and Jerry Lakes are dimictic with complete mixing by wind having occurred during late November of 1973 and early May of 1974. Water temperatures in the lakes differed little with maximum epilimnetic temperatures ranging between 20 and 24C during July and August (Fig. 3 and 4). Maximum rates of temperature decrease (up to 7.5C per m) within the metalimnia were found during July. The lower limit of the metalimnion in both lakes was at approximately 9.5m by the third week of May and had moved downward to 11.5m by mid-October. The corresponding mean rates of change of the volumes of the hypolimnia during a 178 day period of thermal stratification were 5.17 x 10^3 m^3 day^{-1} and 4.18 x 10^3 m^3 day^{-1}, or changes of 16% and 19% of the total hypolimnetic volumes in Harp and Jerry Lakes, respectively. No attempts were made to calculate annual or seasonal heat budgets for Harp or Jerry Lakes, but neither lake is characterized by peculiar features suggesting annual heat budgets different from those of any other lake of similar area, mean depth and latitude (see Schindler (1971) for a discussion of factors affecting heat budgets of Precambrian Shield lakes in northwestern Ontario). Both lakes cooled to 3C during the late autumn period of circulation and surface ice formation had begun by late December. Maximum ice thickness of 62 cm was attained in late February. Accumulations of snow on top of the lake ice were minimal (usually less than 20 cm) and much of the increment to ice thickness resulted from the freezing of snow melt on the ice surface after winter thaws. The lakes became free of ice by the last week of April and surface water temperatures had warmed to 14C by the end of May (Fig. 3 and 4).

Both Harp and Jerry Lakes were characterized by similar distributions of dissolved oxygen (Fig. 3 and 4); however, hypolimnetic depletion was somewhat more severe in Jerry Lake during the autumn stagnation period when concentrations less than 0.5 mg/l were recorded from depths below 22m. On the other hand, concentrations were 1 mg/l or less below 32m in Harp Lake on the same date. Both lakes exhibited a positive heterograde distribution of dissolved oxygen in early summer with metalimnetic maxima to 10 mg/l. There are no early summer data on vertical distribution of phytoplankton for either lake; however, composite samples collected through the euphotic zones (which

included the metalimnion) contained a relative abundance of chroococcalean blue-green algae, especially in Harp Lake, most of which was likely collected from the metalimnion, based on experience in other Shield lakes (Ontario Ministry of the Environment, unpublished data). These are the most likely origin of the metalimnetic maxima in dissolved oxygen observed during the early summer period. During both the ice-free and ice covered periods, dissolved oxygen concentrations in the surface waters of Jerry Lake were generally slightly lower than in Harp Lake, perhaps owing to respiration by bacteria associated with humic compounds in the more highly coloured waters of Jerry Lake as suggested by Smith (1961) and Kerekes (1974) for brown water lakes of Newfoundland. In fact, bacteriological investigations of the lake during the summer of 1973 showed total heterotrophic bacteria to be generally more abundant in the surface waters of Jerry Lake than in Harp Lake (G. Hendry, unpublished manuscript).

It is of interest to compare rates of dissolved oxygen depletion, integrated with depth, for the two lakes. Under winter ice cover (calculated for the period January 1 to April 4) dissolved oxygen depletion was somewhat higher in Jerry Lake averaging 0.020 mg/l·day or 273 mg/m^2·day in contrast to Harp Lake's 0.016 mg/l·day or 224 mg/m^2·day. Volumetric depletion rates are similar to those recorded under ice in several lakes in the Experimental Lakes Area of northwestern Ontario (Schindler 1971); however, areal depletion rates under ice in Harp and Jerry Lakes were generally several times greater, owing to their greater depths.

Harp and Jerry Lakes had very similar hypolimnetic areal depletion rates during the summer stagnation period at 340 and 342 mg/m^2·day, respectively; but, Jerry Lake's dissolved oxygen deficit per unit hypolimnetic volume (0.041 mg/l·day) was again somewhat greater than the 0.033 mg/l·day found for Harp Lake. Hypolimnetic areal dissolved oxygen depletion rate has been used by Mortimer (1941) and Hutchinson (1957) as an index of the trophic state of lakes. Hutchinson's upper limit for oligotrophy is 170 mg/m^2·day and he suggests a lower limit of 330 mg/m^2·day for eutrophy while Mortimer's limits were 250 and 550 mg/m^2·day for oligotrophy and eutrophy, respectively. The areal depletion rate for the hypolimnion of the central basin of Lake Erie is about 390 mg/m^2·day (Burns and Ross 1972) and hence falls within the criteria suggested by Hutchinson for eutrophic lakes and by Mortimer for mesotrophic lakes. Similarly Harp and Jerry Lakes might be considered mesotrophic according to the guidelines suggested by Mortimer and eutrophic, according to Hutchinson's criteria.

In view of Lasenby's (1975) model of dissolved oxygen depletion relating Secchi disc visibility to areal hypolimnetic oxygen deficit, it is of particular significance that the higher oxygen depletion rates of Jerry Lake coincided with a lower mean Secchi disc value and higher rates of sedimentation of total solids, organic matter, total N and total P (Fig. 5 and 6). Similarly, Lappalainen (1972) found a relationship between net sedimentation rate of P and late summer hypolimnetic dissolved oxygen content in several basins of Lake Päijänne, Sweden.

Because hypolimnetic temperatures in Harp and Jerry Lakes do not differ appreciably from winter to summer, similar rates of dissolved oxygen depletion might be expected during both the ice-free and ice-covered seasons given constant supplies of oxidixable sedimenting materials. However, hypolimnetic dissolved oxygen depletion rates were twice as high during summer as during winter owing mainly to ice-free period rates of organic matter sedimentation averaging 2-3 times higher in Harp and Jerry Lakes than during the ice-covered period.

Physico-Chemical Characteristics

The waters of both lakes and inflowing streams were generally very similar in concentrations of mineral constituents (Table 2). Concentrations of major ions (as well as specific conductance) of the euphotic zone of the lakes are comparable to those of some of the most dilute lakes of the world (for a summary, see Armstrong and Schindler 1971, Table 10).

Pronounced seasonal trends in specific conductance, iron, alkalinity, hardness and pH in the euphotic zone, bottom waters and outflow of Harp Lake were not apparent; however, a trend to higher alkalinity in the euphotic zone of Jerry Lake (9-11 mg/l as $CaCO_3$) was evident in late fall and early winter about six weeks after a seasonal alkalinity peak in the inflow (Fig. 7). Lowest euphotic zone alkalinity in Jerry Lake was found in spring, ranging from 3-6 mg/l. Springtime euphotic zone alkalinity was somewhat higher in Harp Lake (ranging from 6-8 mg/l) and the late fall peak was not as well defined as in Jerry Lake.

The colour of Jerry Lake, ranging between 5 and 60 Hazen Units in the euphotic zone, averaged about three times greater than Harp Lake (Table 2). The differences are undoubtedly related to allochthonous contributions with

Table 2: Mineral and organic constituents of Harp and Jerry Lakes, May 1973 to May 1974.

		HARP LAKE						JERRY LAKE					
		Ice-free			Ice-on (a)			Ice-free			Ice-on		
		Mean	Range	Freq.	Mean	Range	Freq.	Mean	Range	Freq.	Mean	Range	Freq.
Specific Cond. (25°C; µmhos/cm)	inflow	40	32-48	21	44	39-49	3	38	32-47	22	44	43-44	3
	outflow	35	34-37	23	42	40-45	4	39	35-47	19	40	28-45	4
	euphotic zn	36	34-39	23	39	38-41	4	38	36-53	22	39	33-43	4
	1 m above btm	37	34-44	23	37	36-39	4	42	38-48	22	37	28-42	4
Alkalinity (as mg/l $CaCO_3$)	inflow	11	6-19	20	7	6-8	3	8	5-13	22	7	6-8	3
	outflow	6	5-9	22	6	5-7	4	7	4-9	19	6	4-8	4
	euphotic zn	7	4-12	23	7	6-7	4	7	4-14	22	7	5-9	4
	1 m above btm	6	4-9	23	7	6-8	4	7	5-10	22	6	5-7	4
Hardness (as mg/l $CaCO_3$)	inflow	17	12-24	17	18	16-20	2	19	12-42	18	14	13-16	3
	outflow	15	11-19	19	15	12-20	4	16	12-20	12	15	13-20	4
	euphotic zn	14	12-18	20	15	12-20	4	17	12-26	11	15	12-20	4
	1 m above btm	15	12-19	20	14	11-20	4	18	14-22	12	13	5-20	4
pH	inflow	6.4	5.6-7.0	22	6.2	5.6-6.7	4	6.3	5.9-7.0	20	5.9	5.6-6.3	3
	outflow	6.3	5.3-7.1	22	6.2	5.9-6.5	4	6.6	6.0-7.0	17	5.9	5.706.0	4
	euphotic zn	6.4	5.8-7.0	22	6.3	6.0-6.7	3	6.6	6.1-7.0	19	6.0	5.7-6.2	4
	1 m above btm	5.7	4.9-6.6	22	6.3	6.1-6.4	4	6.1	5.5-6.8	19	5.9	5.6-6.1	4
Total Iron (mgFe/l)	inflow	0.60	0.15-2.1	21	0.85	0.35-1.4	3	0.77	0.25-1.1	22	0.60	0.25-1.1	3
	outflow	0.18	<0.05-0.45	22	0.14	0.10-0.45	4	0.11	0.05-0.30	19	0.38	0.05-1.0	4
	euphotic zn	<0.05	<0.05-0.15	23	0.05	<0.05-0.10	4	0.19	0.05-1.8	22	0.25	0.20-0.30	4
	1 m above btm	0.29	0.05-0.75	20	0.34	0.20-0.45	4	1.2	0.15-3.2	22	0.40	0.05-0.55	4
Chloride (mg/l)	inflow	<1	<1 - 3	13	<1	<1 - 3	3	<1	<1 - 3	7	<1	<1 - 2	3
	outflow	<1	<1 - 3	15	<1	<1 - 2	3	<1	<1 - 3	7	<1	<1 - 2	3
	euphotic zn	<1	<1 - 2	10	<1	<1 - 3	3	<1	<1 - 3	6	<1	<1 - 2	3
Sulphate (mg/l)	inflow	10	7-12	8	-	-	-	11	9-14	6	-	-	-
	outflow	10	9-12	8	-	-	-	10	10-12	6	-	-	-
	euphotic zn	10	9-12	7	-	-	-	10	9-14	7	-	-	-
Sodium (mg/l)	euphotic zn	<1	<1-2	6	-	-	-	<1	<1-2	5	-	-	-
Potassium (mg/l)	euphotic zn	<1	<1-1.2	6	-	-	-	<1	<1-1.2	5	-	-	-
Magnesium (mg/l)	euphotic zn	<1	<1-2	6	1	<1-2	4	<1	<1	5	<1	<1-3	4
Calcium (mg/l)	euphotic zn	3	2-5	6	3	2-5	4	4	4-5	5	4	3-4	4
Total Organic Carbon (mg/l)	inflow	12	9-13	4	9	8-10	2	15	8-21	5	8	6-9	2
	outflow	8	6-11	5	8	7-9	3	10	7-11	4	6	3-11	3
	euphotic zn	9	4-16	4	7	5-9	3	10	7-15	5	6	5-9	3
	1 m above btm	8	5-11	4	6	5-8	3	9	8-11	5	5	1-9	3
Colour (Hazen Units)	inflow	43	40-50	5	30	20-40	3	121	100-175	6	60	60	2
	outflow	10	5-15	4	11	5-15	3	14	5-20	6	18	5-30	3
	euphotic zn	8	5-20	5	10	5-30	3	23	5-60	6	25	15-30	3
	1 m above btm	9	5-20	5	11	5-15	3	90	60-125	6	22	5-30	3

(a) Under winter ice cover, the euphotic zone results are from samples collected at 5 m.

the more highly coloured stream inflow to Jerry Lake (and greater volume of flow - see below) ranging in colour from 100 to 175 Hazen Units and Harp Lake's major inflowing stream ranging from 40 to 50 Hazen Units during the ice-free period. The colour of Jerry Lake is similar to that of arctic lakes receiving drainage from peat deposits (Kalff 1968) and is probably related to areas of flooded organic soils observed to have been created by beavers within the Jerry Lake drainage basin. Colour data are too few to determine seasonal trends or to correlate with rainfall as Kerekes (1974) has done for Newfoundland lakes. The outflows of both Harp and Jerry Lakes were less coloured than the inflows (Table 2) and suggests oxidation or sedimentation within the lakes of a portion of the inflowing humic compounds.

Total iron and total organic carbon concentrations in the Jerry Lake inflows were also higher than in the Harp Lake stream inflow (Fig. 7 and Table 2). Although data are few, stream concentrations of iron during the winter period of ice cover were relatively high and surface lake water values (5m, under ice) in Jerry Lake were somewhat higher than during the ice-free period averaging 0.19 mg/l and 0.25 mg/l during the ice-free and ice covered periods, respectively (Fig 7 and Table 2). The bottom waters of Jerry Lake were considerably higher in iron than in Harp Lake during the summer stagnation period reaching a high of 3.2 mg/l at 1m above bottom on October 19, in contrast to Harp Lake's maximum of 0.75 mg/l. Iron concentrations in the euphotic zone of Harp Lake were most often below or near the limit of analytical detection (0.05 mg/l) during both the ice covered and ice-free periods.

A seasonal trend in iron was apparent in the Jerry Lake inflow with lowest concentrations during the late spring and late fall ranging from 0.25 to 0.45 mg/l and highest concentrations found during mid and late summer and during late winter ranging from 0.85 to 1.1 mg/l (Fig. 7). Iron concentrations decreased slightly after heavy rainfall (60 mm) during the last week of July following almost four weeks of dry weather (Fig. 7). A similar seasonal trend in iron on the Harp Lake inflow was evident; however, mid-summer concentrations were lower ranging from 0.50 to 1.0 mg/l, while higher iron concentrations were found in the Harp inflow following the heavy late July rainfall (Fig. 7).

Seasonal trends were also evident in other mineral constituents especially alkalinity and hardness with highest values found during late

summer. Alkalinity (Fig. 7) and hardness (Table 2) values were higher in the Harp Lake inflow than the Jerry Lake inflow during this period. The seasonality of specific conductance in the inflowing streams (Fig. 7) closely resembled that of iron with lowest values found during early summer and highest values during late summer and winter.

The frequency of analyses of major cations and anions was too low to indicate seasonal trends, but chloride and the major cations were very similar in concentrations (Table 2) to those of other waters of the Precambrian Shield (Armstrong and Schindler 1971; Schindler and Nighswander 1970; Ontario Ministry of the Environment, unpublished data). Sulphate concentrations averaging about 10 mg/l in Harp and Jerry Lakes were much higher than those of Shield lakes in northwestern Ontario (Armstrong and Schindler 1971). In Clear Lake in southeastern Ontario, Schindler and Nighswander (1970) also found relatively high sulphate concentrations (0.168 meg/l or about 8 mg/l). Nicholls and Cox (1976) found the pH of 14 rainfall samples collected over Harp Lake to range from 3.2 to 5.1 with a calculated median value of only 3.9. It is therefore probable that the difference in sulphate concentrations between northern and southern Ontario Precambrian Shield lakes is related more to proximity to industrialized urban areas and atmospheric sulphur dioxide fallout than to differences in bedrock geology.

Sulphate concentrations in Char Lake in the Canadian arctic (Schindler et al. 1974) are as high as those of Harp and Jerry Lakes and although potassium concentrations are similar as well, the relatively high sulphate values of Char Lake are more likely related to drainage from sedimentary rock (as indicated by much higher Ca and Mg concentrations) rather than by atmospheric contributions. With respect to major cations and specific conductance, Harp and Jerry Lakes are also similar to Precambrian Shield lakes in Newfoundland (Kerekes 1974). However, sulphate concentrations in the Ontario lakes are about 2-4 times higher than in the Newfoundland lakes.

Some evidence for "freezing out" of major mineral constituents during early winter ice formation was indicated by conductivities 2-5 μmhos/cm higher at 1m below ice than in the remainder of the water column in both Harp and Jerry Lakes. Furthermore, specific conductance of the lower lake ice (sectioned with a saw, melted and analyzed) was low at 10-12 μmhos/cm and rough calculations indicated that the decrease could be accounted for

by the increased conductivity of the water beneath the ice. Much higher relative values (up to 9 μmhos/cm greater at 1m below ice) found in early March were more likely related to stream contributions during the early spring thaw than to "freezing out" of mineral constituents.

Nutrients

Nitrate-N was the dominant form of inorganic nitrogen while ammonia-N concentrations were often below the limit of analytical detection (10 μg/l) in inflowing streams of both Harp and Jerry Lakes (Table 3). Concentrations of inorganic nitrogen were highest in the Harp and Jerry Lake inflows during late winter and early spring (up to 460 μg N/l on Harp and 740 μg N/l on Jerry) and lowest (<10 μg N/l) during October and November. Although a trend to lower concentrations of total Kjeldahl-N was noted in the inflowing and outflowing streams, euphotic zone and bottom waters of both lakes during the spring runoff period, no pronounced trends were evident during the other seasons of the year. Total Kjeldahl-N concentrations were slightly higher in Jerry Lake than in Harp Lake (Table 3).

Despite depletion of dissolved oxygen in the bottom waters of both lakes by late fall no late summer or autumn accumulations of either nitrate-N or ammonia-N were evident in the bottom waters of either lake, although nitrate-N concentrations were consistantly higher than ammonia-N in both lakes and bottom water nitrate-N concentrations were slightly higher in Jerry Lake than in Harp Lake (Table 3). Analyses for ammonia-N and nitrate-N were too infrequent on euphotic zone and outflow water samples collected during the summer to determine seasonal trends of inorganic N in the surface water of either lake; however, summer concentrations may often have been only slightly above the lower limit of analytical detection (10 μg N/l) as judged from the few data available (Table 3). Winter and spring concentrations of ammonia-N in the euphotic zone of Harp and Jerry Lakes were still low, but nitrate-N concentrations were much higher, especially in Jerry Lake, and the differences were undoubtedly related to higher concentrations in the Jerry Lake inflow during this time of the year (Table 3).

Euphotic zone concentrations of total phosphorus generally ranged between 5 and 20 μg P/l in both lakes (Fig. 8) and are similar to concentrations found in many other Shield lakes of Ontario (Ontario Ministry of the

Table 3. Nitrogen concentrations of Harp and Jerry Lakes, May 1973 to May 1974. When mean values are meaningless, they are not given.

		HARP LAKE						JERRY LAKE					
		Ice-free			Ice-on			Ice-free			Ice-on		
		Mean	Range	Freq.	Mean	Range	Freq.	Mean	Range	Freq.	Mean	Range	Freq.
Total Kjeldahl Nitrogen (mg/l)	inflow	0.47	0.23-1.3	22	0.44	0.33-0.52	3	0.68	0.33-1.2	20	0.59	0.45-0.86	3
	outflow	0.29	0.23-0.52	23	0.25	0.23-0.27	4	0.34	0.24-0.57	19	0.32	0.29-0.36	4
	euphotic zn	0.24	0.18-0.48	24	0.25	0.23-0.26	4	0.30	0.25-0.40	22	0.28	0.25-0.35	4
	1 m above btm	0.25	0.20-0.48	24	0.22	0.20-0.25	4	0.34	0.23-0.52	22	0.35	0.23-0.54	4
Ammonia Nitrogen (μg/l)	inflow	-	<10 - 130	24	90	30 - 120	3	-	<10 - 240	21	110	50 - 130	3
	outflow	-	<10 - 80	7	20	10 - 30	4	-	<10 - 80	9	70	10 - 220	4
	euphotic zn	-	<10 - 80	8	20	10 - 40	4	40	<10 - 100	13	30	10 - 90	4
	1 m above btm	-	<10 - 140	24	-	<10 - 10	4	-	<10 - 130	22	-	<10 - 320	4
Nitrate Nitrogen (μg/l)	inflow	90	<10 - 250	24	260	170-340	3	-	<10 - 160	21	320	130-600	3
	outflow	-	<10 - 40	7	150	100-200	4	-	<10 - 150	7	250	50-410	4
	euphotic zn	-	<10 - 50	8	90	60-120	4	40	<10 - 80	11	190	70-260	4
	1 m above btm	120	<10 - 260	24	90	40-120	4	190	60 - 430	22	240	70-580	4
Nitrite Nitrogen	inflow	5	1 - 9	24	6	5 - 7	3	9	5 -28	21	6	5 - 7	3
	outflow	-	1 - 3	7	3	2 - 4	4	-	2 - 5	7	3	2 - 4	4
	euphotic zn	-	2 - 4	8	4	2 -10	4	4	2 - 6	11	3	2 - 3	4
	1 m above btm	3	1 -10	24	3	2 - 4	4	4	1 - 8	22	3	2 - 4	4

Environment unpublished data; Dillon and Rigler 1974). Total phosphorus concentrations in the Jerry Lake and Harp Lake inflows averaged approximately 50 μg P/l and 30 μg P/l during the ice-free period, respectively (Fig. 9). lowest concentrations (commonly ranging from 5 to 20 μg P/l) were found in late winter in the Harp Lake stream inflow. In contrast to the inflow, generally lower P concentrations, much less fluctuation and little evidence of seasonal variations were found in the outflows of both lakes (Fig. 10).

A slight trend to higher bottom water concentrations of total P in Jerry Lake was noted during the latter stages of summer stagnation (Fig. 11) and corresponded with the increase in iron (to 3.2 mg/l) noted above. Although some of the observed accumulations of Fe and P may have resulted from reduction and solubilization of ferric phosphate complexes, most of the observed increases probably resulted from sedimentation from the euphotic zone since dissolved oxygen depletion apparently was not severe enough or prolonged enough to lead to accumulations of ammonia-N.

Reviews by Lee (1970), McKee et al. (1970a, 1970b) and Golterman (1973) on the subject of sediment-water nutrient relationships indicate that literature pertaining to nutrient feedback from lake sediments is somewhat confused. Several authors including Einsele (1936) and Mortimer (1941-42) and more recently Schindler and Comita (1971), Hynes and Greib (1970), Gahler (1969) and Burns and Ross (1972) have documented significant release of nutrients from anaerobic lake bottom muds. On the other hand, Schindler et al. (1974) found no release of either N or P from the sediments of eutrophic Meretta Lake in the Canadian arctic despite high loadings of N and P to the lake from sewage, although bottom water dissolved oxygen was never completely depleted. Additionally, Schindler et al. (1973) found no return of phosphorus from the anoxic bottom sediments of Lake 227 (a Precambrian Shield lake in northwestern Ontario) even following four years of artificial nutrient additions to the lake. No apparent accumulations of phosphorus, nitrogen or iron materialized in the bottom water of Stony Lake (Kawartha Lakes district of Ontario) during the summer and autumn stagnation period of 1971 despite severe hypolimnetic anoxia; yet, MacLean Lake (a southern Ontario Precambrian Shield lake investigated during 1973) showed bottom water concentrations reaching 12 mg Fe/l, 0.49 mg total P/l and 1.2 mg NH_3-N/l late in the stagnation period (Ontario Ministry of the Environment, unpublished data). In view of such dissimilar findings, it would appear to

be unwise to make predictions regarding nutrient feedback from lake sediments based solely on hypolimnetic dissolved oxygen data; nevertheless, the lack of iron accumulation in the bottom waters of Harp Lake relative to the high concentrations in Jerry Lake in October may be related to the less severe hypolimnetic oxygen depletion in Harp Lake (Fig. 6) and, as well, to lower rates of iron input from the Harp Lake catchment.

Soluble reactive silicate (silica) concentrations were relatively high in the inflowing streams with maxima of 15.0 mg SiO_2/l and 10.0 mg/l in the Harp and Jerry inflows, respectively (Table 4) and are comparable to concentrations draining sedimentary soils of agricultural watersheds of southern Ontario (Nicholls and MacCrimmon 1975; Kelso and MacCrimmon 1969). Concentrations in the outflows and euphotic zones of both lakes were much lower, most likely indicating incorporation into diatom frustules and subsequent sedimentation within the lakes. Analyses were too infrequent to accurately define seasonal trends; however, lake and stream concentrations were highest in winter and inflowing stream concentrations were lowest during the spring runoff period.

Samples collected from six depths between the surface and 2 x the Secchi disc depth on four occasions in July and August in conjunction with primary production experiments revealed very low concentrations of inorganic carbon ranging from 0.4 to 3.0 mg C/l in Jerry Lake and from 0.5 to 2.1 mg C/l in Harp Lake. Highest concentrations were found at the lower level of the euphotic zones of both lakes and undoubtedly indicate lower rates of inorganic carbon assimilation by phytoplankton than at the surface or at mid-euphotic zone depths where concentrations were lowest. Sample collections were all made about mid-day and changes in concentrations of inorganic carbon occurring throughout the day were not investigated. Large diurnal fluctuation of inorganic carbon of up to ten times as found by Schindler and Fee (1973) is likely only common to highly enriched and productive soft water lakes and is probably not an important phenomenon in Harp or Jerry Lakes.

Hydrologic Budget

Owing mainly to difficulty of access (especially Jerry Lake), flow measurements were not made frequently enough to accurately develop hydrographs from field measurements alone. The longest period of consecutive daily flow measurements of Harp Lake's inflow and outflow was from May 1 to June 6, 1974

Table 4: Soluble reactive silicate (as mg SiO_2/l) in Harp and Jerry Lakes, May 1973 to June, 1974.

		Harp Lake						Jerry Lake					
		Ice Free			Ice-On			Ice Free			Ice-On		
		Mean	range	freq.	Mean	range	freq.	Mean	range	freq.	Mean	range	freq.
	inflow	8.3	4.8-15.0	11	8.3	6.8-10.0	3	4.1	0.5-6.1	13	8.4	7.3- 9.8	3
SiO_2	outflow	1.7	0.5- 2.5	11	3.8	2.9- 6.0	4	2.9	1.8-4.3	10	5.5	1.1- 9.6	4
(mg/l)	euphotic zone	1.7	0.8- 2.6	12	2.0	1.9- 2.3	4	3.2	2.2-4.2	13	5.5	3.2-10.0	4
	1m above bottom	3.6	1.9- 7.6	12	4.0	2.6- 6.6	4	5.4	3.5-7.0	13	4.7	0.2- 8.8	4

and allowed comparison of Harp Lake flow data with the hydrograph of the nearby Rosseau River which was monitored daily by the Ministry's Hydrologic Data Section, but for another project. Well defined relationships existed between Harp Lake inflow and outflow rates and Rosseau River flow rates following a peak in their hydrographs in mid-May (Fig. 12 and 13) when daily flow readings were available from both locations. The Harp Lake inflow data were one day out of sequence with the Rosseau River data owing to the quicker response of the smaller stream to rainfall. On the other hand, Harp Lake outflow data suggest that storage capacity of the lake compensates to some extent for the lag in the response time of the Rosseau River following rainfall since the best relationship between flows at the two sites was obtained when coincident data were plotted. With some extrapolation beyond the range of the plotted points, Fig. 12 and 13 were used to develop more complete hydrographs of Harp Lake's inflow and outflow (Fig. 14 and 15).

Similarly, correlations between Harp and Jerry Lakes' inflows and outflows (Fig. 16 and 17) were used to fill in missing data and develop hydrographs of Jerry Lake's inflow and outflow (Fig 18 and 19) where field measurements were made less frequently than on Harp Lake.

The total water volume from annual land runoff to each lake (q_t) was calculated as follows:

$$q_t = (q_m + q_u) = Q_T - [(Pr-Ev)]$$

where q_m = runoff from the monitored catchment (measured)

q_u = runoff from the unmonitored catchment (not measured; obtained by difference)

Q_T = runoff (outflow) from the total lake basin (measured)

Pr = precipitation falling on the lake (measured at Huntsville)

Ev = evaporation from the lake (not measured; long term average assumed)

Assuming an annual evaporation loss of 65 cm - the long term average for Muskoka area lakes (Bruce and Weisman, 1966) and a total precipitation of 106.5 cm during the study period (recorded at Huntsville, 8 km west, south-west), annual land runoffs to Harp and Jerry Lakes from their total catchments (Table 5) were calculated to be 0.67m and 0.64m, respectively (Table 6). Total precipitation during the annual period of measurement was 16% higher than the long-term average (91.7 cm) and probably accounted in part for the higher measured annual runoff from the lake basins over the long-term average

Table 5: Areas of components of the Harp and Jerry Lake basins including those catchments drained by streams monitored for nutrient concentrations and flow.

	km²				
	total basin	total catchment	monitored catchment	unmonitored catchment	lake
Harp Lake	4.74*	3.99*	0.55*	3.44	0.75
Jerry Lake	7.87	7.32	3.63	3.69	0.55

* This is likely an underestimate. The area will be checked during 1976. However, any changes in monitored catchment area do not affect calculations of the P balance (see Appendix 5).

Table 6: Summary of annual hydrologic budgets for Harp and Jerry Lake basins, June 20, 1973 to June 21, 1974.

	INPUT ($X10^6$ m^3)				OUTPUT ($X10^6$ m^3)	
	Land Drainage[1]			Precipitation		
	monitored catchment	unmonitored catchment	total catchment		Outflow (total basin)	Evaporation
Harp Lake	0.783	1.882	2.665	0.798	2.976	0.487
Jerry Lake	3.152	1.540	4.692	0.589	4.922	0.360

[1]Annual Land Runoff (m)

Harp Lake: 0.67

Jerry Lake: 0.64

of 0.50 m/yr given by Pentland (1968) for this region of Ontario.

A discussion of possible errors in measurements and calculations of the hydrologic (and phosphorus) budgets and their implications to the calculations of the phosphorus input associated with cottages is presented in Appendix 5.

Phosphorus Budgets

(a) Natural land drainage and aeolian inputs.

The annual study period was divided into 39 time periods varying in length from two to 25 days in accordance with the frequency of data collection. Phosphorus inputs and outputs at the stream monitoring locations of both lakes were calculated by multiplying weighted mean total P concentrations during each of the time periods by total flow during each time period as calculated by planimetry from linear plots of the hydrographs.[1]

P loading per unit runoff was slightly higher from Jerry Lake's catchment (29.8 mg/m^3) than from Harp Lake's catchment (27.6 mg/m^3) and may have been related to the presence of flooded peaty soils associated with beaver ponds which were not present within Harp Lake's monitored catchment.

To obtain total loading data from land drainage (excluding cottages) to both lakes (Table 7), extrapolation to the P loading to the lakes from their unmonitored catchments was as follows:

(1) the total water equivalent of the winter precipitation (December to May) falling on the unmonitored catchments was assumed to run off between April 4 and April 30 (as judged from the inflow hydrographs).

(2) a weighted mean concentration of 23.7 mg P/m^3 as determined for Harp Lake's inflow during the April 4-30 period was assumed for the runoff from unmonitored areas.

(3) the water export from the unmonitored areas for the remainder of the annual study period was obtained by difference (input + precipitation on lake = output + evaporation from lake) and a ground water concentration of 5 mg P/m^3 was assumed for this amount.

Specific exports of P from Harp and Jerry Lake's total drainage basins of 15.0 and 18.3 mg/m^2 yr, respectively (Table 7) are about one-half as high as P export values found for mixed agricultural-woodland areas of southern Ontario (Nicholls and MacCrimmon 1975; Owen and Johnson 1966); however, they are considerably higher than the 4.8 $mg/m^2 \cdot yr$ suggested by Dillon and Kirchner (1975) for igneous, forested watersheds in Ontario. Annual runoff during the study period, which was about 30% higher than the long-term average, undoubtedly accounted in part for the high P export values from the Harp and Jerry Lake drainage basins. Suspended particulate P derived from land runoff may have been important in the inflowing streams and likely also contributed to the high P export as well, since total P concentrations in the inflows fluctuated widely during the period of maximum flow in late winter and spring and were in contrast to the much lower concentrations characterizing the lakes' outflows during the same period.

Nicholls and Cox (1976) have reported an aeolian contribution of N and P (in precipitation and dry fallout) as measured over most of the ice-free period (32 separate rainfalls) in a collector installed on a rocky shoal of Harp Lake and during the winter from precipitation samples collected on the lake ice surface. The total P loading from the atmosphere was calculated to be 74 mg P m^2 yr and is in excellent agreement with the 77 $mg/m^2 \cdot yr$ found by Dillon (1974) in the Haliburton Highlands area (a few km east of the Harp and Jerry Lake area). During the annual study period, total aeolian P loadings of 55.8 and 41.2 kg P (Table 7) comprised 43 and 23% of the total P loadings from natural sources (aeolian plus land drainage) to Harp and Jerry Lakes, respectively.

Table 7 : Partial summary of annual phosphorus budgets for Harp and Jerry Lakes, June 20, 1973 to June 21, 1974.

	INPUT (kg)					OUTPUT (kg)
	[1] Land Drainage			Atmosphere	Total	monitored outflow (total basin)
	monitored catchment	unmonitored catchment	total catchment			
Harp Lake	21.6	38.4	60.0	55.8	115.8	46.5
Jerry Lake	94.2	39.4	133.6	41.2	174.8	75.8

[1] Specific export (mg P/m^2•yr)

Harp Lake: 15.0

Jerry Lake: 18.3

(b) Inputs to Harp Lake from cottages

A widely recognized P balance equation for lakes may be summarized as:

$J_T = O_T + B + r_{net} + \frac{dc}{dt} V$, where

J_T = total P supplied to the lake

O_T = total P lost through lake outflow

B = P removed from solution or suspension by biota in trophic levels higher than plankton

r_{net} = net retention of P

$\frac{dc}{dt}$ = concentration change of P per unit time

V = volume of lake

and which may be further reduced to

$$r_{net} = J_T - O_T$$

since B and $\frac{dc}{dt}$ are negligible relative to r_{net}, J_T and O_T

(Vollenweider 1969, 1975; Lappalainen 1972).

Since Fuhs' (1973) data show that changes in P concentration associated with biomass are negligible compared with sedimentation losses of P (also supported by Vollenweider (1969, 1975) and Lappalainen (1972), it can be assumed that annual net retention of P calculated as $J_T - O_T$ is closely approximated by annual net sedimentation (S_{net}). The P mass balance equation for Harp Lake can therefore be written as:

$$J_E + J_{PR} + J_A = O_T + S_{net}$$

and for Jerry Lake

$$J_E + J_{PR} = O_T + S_{net}$$

where $J_E + J_{PR} + J_A = J_T$, and J_E = total P supplied from natural land drainage, J_{PR} = total P supplied from the atmosphere, and J_A = total P supplied from cottaged lots.

It was recognized that gross sedimentation rate as measured in sedimentation traps was likely to be different from net sedimentation rate as determined by the difference between the total P input and output, owing to probable errors in measurement, in trap design and to recycling and resuspension of sedimented material. Gross sedimentation rate was measured in both Harp and Jerry Lakes in order to derive the ratio of S_{gross}-to-S_{net} for Jerry Lake which could be applied to Harp Lake.

An important assumption leading to the calculation of J_A is that both lakes have the same S_{gross}-to-S_{net} ratio. Considerable confidence should be had in this assumption since sedimentation traps were exposed concurrently for identical times (five exposures during winter and summer stagnation periods totalling 70 days) and at identical depths. The same factors contributing to S_{net} therefore also contributed to S_{gross}; so, if S_{gross} for Jerry Lake is higher than for Harp Lake, S_{net} should also be proportionately higher. It is of little consequence to the calculation of J_A what the S_{gross}-to-S_{net} ratio is, but only that it is the same for both lakes (see Appendix 5).

Annual estimates of total P gross sedimentation rates of 130 and 194 μg P/cm^2/yr in Harp and Jerry Lakes, respectively (Table 8) were derived by extrapolation of the results from summer and winter exposures of the sediment traps to the total ice-free and ice-covered periods.

Extrapolation of mid-lake sedimentation rates to the whole lake basin are risky, but necessary, if gross and net sedimentation rates are to be compared. Fuhs (1973) assumes that sedimenting particles are produced in the trophogenic zone over an area equal to the area of the trap opening. Whole lake sedimentation is then calculated by multiplying sedimentation per unit volume of the trophogenic zone by the volume of the trophogenic zone. This method probably gives an underestimation because it assumes that all sedimenting materials are of autochthonous origin and ignores that portion of the total P load to the lake which sediments as allochthonous material in littoral areas of the lake. It may be more correct therefore to assume that the lessened autochthonous particle sedimentation in littoral areas owing

Table 8: Sedimentation rate of P as measured in mid-lake hypolimnion and extrapolated to annual gross sedimentation of P in Harp and Jerry Lakes

	Gross Sed. Rate mid-lake ($\mu g\ P/cm^2/yr$)	[1] Trophogenic Zone Volume ($m^3 \times 10^6$)	[2] Total Gross Sedimentation (kg P/yr)	
			I	II
Harp Lake	130	5.32	766	971
Jerry Lake	194	3.73	905	1073

[1] calculated as lake volume between lake surface and a depth of twice the average Secchi disc reading (or to lake bottom in littoral areas)

[2] I - calculated according to Fuhs (1973)

II - calculated assuming mid-lake sedimentation rate over whole lake basin

to shallower trophogenic zone depths (as per Fuhs 1973) is compensated for by greater sedimentation of allochthonous material in littoral areas than in mid-lake areas, with the result that the same sedimentation rate per unit lake area as determined from mid-lake trap data can be applied to inshore as well as offshore areas. Thus, the total gross annual P sedimentation calculated by the latter method and used in subsequent calculations of $\frac{S_{gross}}{S_{net}}$ are 971 kg and 1073 kg P in Harp and Jerry Lakes, respectively (Table 8).

Average daily sedimentation rates of 3.6 mg P/m^2 in Harp Lake and 5.3 mg P/m^2 in Jerry Lake represents about 3.5 percent of the average mass of P per m^2 through the trophogenic zone of each lake and are in good agreement with similarly published studies of sedimentation (Bloesch 1974; Charlton 1975). In fact, Rigler (1973) points out that a daily loss of trophogenic zone P to lake sediment is remarkably constant at 1-3% in a variety of lake types.

Given the measured total P supply to Jerry Lake of 175 kg P/yr and the total loss from the lake (O_T) through the outflow of 76 kg P/yr, the S_{net} of 99 kg P/yr is only 9.2% of the S_{gross} (1073 kg P/yr) measured in sedimentation traps, or $\frac{S_{gross}}{S_{net}}$ = 10.8 and is in good agreement with Fuhs' (1973) findings. From May to December on Canadarago Lake, Fuhs (op-cit.) showed that P sedimenting into traps suspended in the hypolimnion exceeded the difference between the measured total input of P to the lake and outflow from the lake by about 10 times. He concluded that incoming P was recycled 10 times between the trophogenic zone and lake sediment during the May to December period. Similar conclusions can probably be drawn for Jerry Lake.

It should be emphasized that recycling rate as used here is the rate of exchange between trophogenic zone and lake bottom determined as the ratio of the rates of S_{gross}-to-S_{net} where S_{gross} is measured in traps and S_{net} is determined as the difference between total input and total output; it is not the same as P turnover rate as used for example by Rigler (1964) to mean the rate at which P is assimilated and in turn released at a specified trophic level and does not necessarily involve sedimentation.

It is of interest to speculate on the mechanisms of P recycling (supposedly eleven times per year) between Jerry Lake's bottom sediment and its trophogenic zone. The tendency for P (and much more obviously, iron) to accumulate in near-bottom waters of Jerry Lake during the late summer stagnation period was noted earlier. Periodic sampling at one, two and three m above bottom in Jerry Lake and experience in other chemically stratified waters (Nicholls and MacCrimmon 1975; unpublished data on Riley and MacLean Lakes) suggests that the concentrations of P decreased rapidly with increasing distance above the lake bottom. It is therefore unlikely that entrainment of metalimnetic and hypolimnetic water into the trophogenic zone of Jerry Lake was an important recycling mechanism as has been suggested for shallower, more eutrophic lakes (Blanton 1973). In fact, rough calculations show that with the volume of Jerry Lake's epilimnion having increased by approximately 6.27×10^5 m^2 between May and October, the resulting entrainment of P into the epilimnion during the period of thermal stratification could only have been about 9 kg, or less than 1% of the total annual P sedimentation (1073 kg P). As early as 1950, with the use of ^{32}P, Hutchinson and Bowen found mass movement of P between the pelagic and littoral zones of lakes to be a major component of P dynamics in lakes. Processes such as biological release from components within the littoral zone and excretion by zooplankton during diurnal migrations (reviewed by Rigler 1973) must be far more significant in recycling P back into the trophogenic zone of Jerry Lake.

Given the total P supply to Jerry Lake (J_T) of 175 kg P/yr and the total loss from the lake (O_T) through the outflow of 76 kg P/yr, a P retention coefficient (R_p) or 0.566 was measured (as $\frac{J_T - O_T}{J_T}$)

Kirchner and Dillon (1975) found the retention coefficient of P to be more closely related to the areal water load, calculated as the annual lake outflow volume divided by the lake surface area, than to the volumetric water load (lake flushing rate). The R_p for Jerry Lake as calculated by their original predictive equation (Kirchner and Dillon 1975) is 0.57 and by their revised equation (Dillon and Kirchner 1976) is 0.60 - both in excellent agreement with the measured R_p of 0.566

If the S_{net} (or R_p, since $R_p = \frac{S_{net}}{J_T}$) were known for Harp Lake, then the cottages component (J_A) of the total P input to the lake (J_T) could be solved since all other components of the P balance equation ($J_E + J_{PR} + J_A = O_T + S_{net}$) were determined. By substituting $S_{net} = \frac{S_{gross}}{10.8} = (J_{PR} + J_E + J_A) - O_T$, J_A can be shown to equal 20.3 kg P/yr.

The artificial P input thus determined from cottages on Harp Lake (20.3 kg/yr or 0.28 kg/cottage) is 50 percent lower than the value of 0.55 suggested by Dillon and Rigler (1975) for use in their model to estimate the capacity of similar Precambrian Shield Lakes for cottage development. Based on Dillon and Rigler's (1975) estimated supply rate to Muskoka area lakes of 0.8 kg P/capita/yr and 0.69 capita÷yr/yr, the 73 cottages surrounding Harp Lake supplied an estimated 40 kg P (as potential J_A) during the annual study period. The calculated input to the lake of 20.3 kg/yr implies that about 50% of the potential artificial P loading to the lake was retained in septic tank-tile bed systems surrounding the lake.

These findings suggest that a better understanding is needed of P dynamics in soils of the Precambrian Shield before artificial loading of P to lakes from septic tank-tile beds can be predicted with confidence.

II PLANKTON

Phytoplankton-Biomass and Composition

The seasonal distributions of total phytoplankton in both lakes were characterized by maxima in early summer of 8.4 mm^3/l in Harp Lake and 9.9 mm^3/l in Jerry Lake (Fig. 20 and 21). The peaks were out of phase by one sampling

interval (three weeks) however, with Jerry Lake's maximum on June 1 comprised mainly of the diatom Rhizosolenia eriensis var. morsa at 8.9 mm^3/l. R. eriensis var. morsa was also relatively abundant in early June in Harp Lake at 1.9 mm^3/l (Fig. 22), but Harp Lake's early summer phytoplankton maximum was not detected until the June 20 sampling date when Cyanophyceae dominated by Aphanothece spp. (7.1 mm^3/l) were most important. This genus was far more important in Harp Lake than in Jerry Lake throughout the ice-free period (7.4 mm^3/l on August 20) while the other common chroococcalean blue-green alga, Chroococcus spp., although considerably lower in biomass, was more common in mid-summer and less common in late summer and fall in Harp Lake than in Jerry Lake (Fig. 23). Cyanophyceae were well represented in the phytoplankton of Jerry Lake on only one sampling date (August 29) when Aphanothece, Merismopedia and Chroococcus spp. comprised 93% of the total algal biomass of 3.9 mm^3/l (Fig. 21).

Chrysophycean algae were best represented in Jerry Lake during spring and early summer (Fig. 24) by Dinobryon bavaricum, D. sertularia, some small unidentified chrysomonads and Mallomonas spp. (M. pseudocoronata and others). The same or closely related chrysophycean species were present in Harp Lake (D. bacaricum, D. bacaricum var. Vanhoeffenii, D. sertularia var. protruberans, M. pseudocoronata). However, Synura sp. and Chrysosphaerella sp. were also important during mid-summer in Harp Lake (comprising 72% and 86% of chrysophycean biomass on August 3 and August 20, respectively), but were absent (or rare) from Jerry Lake.

Except during early summer, when Ankistrodesmus (mainly A. falcatus), and desmids were more common in Jerry Lake, and during fall and winter when Botryococcus spp. were more common in Harp Lake (Fig. 25), the Class Chlorophyceae was fairly equally represented in both lakes by several other taxa in low densities (e.g. Quadrigula, Gloeocystis, Oocystis, Tetrastrum, Crucigenia, Pediastrum, Chlamydomonas and others). Desmids were a minor component of the total phytoplankton, being represented mainly by Cosmarium and Closterium species (Fig. 25). The only other desmid of importance in the lakes was Arthrodesmus which was confined to the early summer period and peaked once in Harp Lake at 0.10 mm^3/l during late June and twice in Jerry Lake at 0.05 mm^3/l in early June and early July.

In descending order of abundance within the diatom flora of Jerry Lake were: Rhizosolenia eriensis var. morsa, Cyclotella stelligera and Synedra sp. (S. filiformis?) (Fig. 22). In Harp Lake, the group was represented (also

in descending order of abundance) by R. eriensis var. morsa, Tabellaria fenestrata (Fig. 22), Cyclotella stelligera, Snyedra sp. (S. filiformis?) and Melosira distans. It is important to note that T. fenestrata and M. distans were not found in Jerry Lake. Other taxa such as Asterionella formosa, Nitzschia spp. Eunotia zasuminensis, Cyclotella comta and others were present in one or both lakes but were of insignificant biomass.

During the ice covered period, phytoplankton biomass was low, ranging from 0.06 to 0.33 mm^3/l in Jerry Lake and from 0.02 to 0.47 mm^3/l in Harp Lake (Fig. 20 and 21). During periods of maximum winter biomass, Cryptomonas ovata was most abundant in Jerry Lake (Fig. 26) while the green alga, Botryococcus sp. was prominant in Harp Lake (Fig. 25). Throughout the study period Cryptophyceae were generally less abundant in Harp Lake than in Jerry Lake although the same species represented the Class. Cryptomonas ovata and Rhodomonas minuta var. nannoplanctica (Fig. 26) were the most common species, but C. marssonii, C. gracilis and C. phaseolus? were also present.

In summary, the dominant Classes in decreasing order of abundance in Jerry Lake were: Bacillariophyceae (diatoms), Cyanophyceae (blue-green algae), Cryptophyceae, Chrysophyceae and Chlorophyceae (green algae); and in Harp Lake: Cyanophyceae, Bacillariophyceae, Chrysophyceae, Chlorophyceae and Cryptophyceae (Fig. 27). Owing to far greater densities of the blue-green alga, Aphanothece spp. in Harp Lake, and much better representation by the diatom Rhizosolenia eriensis var. morsa in Jerry Lake, the Cyanophyceae and Bacillariophyceae, respectively were unequally represented in the two lakes; however, other dominant classes differed little between the lakes (Fig. 27).

An indication of the eutrophication of Harp Lake relates to the high phytoplankton biomass throughout most of the summer period. The total biomass exceeded 8 mm^3/l on three occasions and averaged 3.9 mm^3/l during the ice-free period and are typical of mesotrophic inshore areas of the Great Lakes (Vollenweider et. al., 1974; Nicholls et. al., 1975). Davis (1964) described a change from bi-modal distribution of phytoplankton to more uniform seasonal distributions including mid-summer maxima as characteristic of the eutrophication process in Lake Erie's Western Basin over the period 1919-1963.

In relatively deep, thermally statified lakes (such as Harp), high mid-summer phytoplankton biomass is unlikely to arise in the absence of external nutrient supplies. This suggests that some of the nutrient input from the cottaged lots around Harp Lake (20.3 kg/yr as determined from comparative P

budgets of Harp and Jerry Lakes) gained access to the lake during the mid-summer (July-August) period which was also when most of the cottages were inhabited. Heavy rainfall (6 cm) during the last few days of July may have facilitated the transfer of nutrients from the cottaged areas.

P Loading to the lake from the monitored inflow stream during July and August, the peak of the cottaging season, was 1.8 kg and when extrapolated to the rest of the catchment, yielded only 4.2 kg P from land drainage exclusive of cottage influence. With total P loading of 0.8 mg/m^2•mm rainfall excluding pollen which was likely unimportant during mid-summer (Nicholls and Cox, 1976), atmospheric loading of P to Harp Lake during the July-August period was likely about 7 kg. Undoubtedly, the combined nutrient inputs from all sources contributed to the high biomass of algae during the mid-summer period but it is significant that mid-summer biomass was low in Jerry Lake where the same natural inputs of P were experienced but where cottages were not present.

Periodic measurements of Secchi disc visibility and chlorophyll a were continued on Harp Lake during 1974 and 1975 (see table below) and indicate

Year	No. of samplings	Secchi disc (m)	Chlorophyll a (µg/l)
1973	66	4.4	2.8
1974	8	3.7	2.1
1975	6	4.9	3.3

considerable year-to-year fluctuation in average Secchi disc and chlorophyll a probably owing to far fewer and non-coinciding sampling dates during the latter two years. Nevertheless, it is significant that there are no well defined trends over the three year period.

Chlorophyll a and Secchi disc data (Fig. 28) also indicate a mesotrophic status of Harp Lake with ice-free period means of 2.8 µg/l and 4.4m falling within the range (2-6 µg/l) chlorophyll a and 3-5m Secchi disc) established for mesotrophic recreational lakes in Ontario (Ontario Ministry of the Environment, unpublished data). Chlorophyll a and Secchi disc ice-free period means of 2.6 µg/l and 3.9m in Jerry Lake (Fig. 20) also indicate mesotrophy (probably erroneously, since the rather poor water transparency of the lake is in large part a result of the brown water colour). Aside from the large early summer biomass of Rhizosolenia eriensis var. morsa (8.9 mm^3/l), most of the other total phytoplankton biomass values recorded over the rest of the study period suggest oligotrophy in Jerry Lake. Moreover, the seasonal distribution of the phytoplankton and the species composition in Jerry Lake seem typical of oligotrophic, humic waters in hard rock areas of the north temperate climate although compara-

tive data are scarce (Ilmavirta and Kotimaa, 1974; Ostrotsky and Duthie, 1975; Plinski and Magnin, 1975).

Another important difference in phytoplankton composition between Harp and Jerry Lakes relates to the occurrence in relatively high densities of *Tabellaria fenestrata* in Harp Lake and its virtual absence from Jerry Lake's phytoplankton. Bonomi *et. al*. (1968) has pointed out that the eutrophication of Lake Maggiori (Italy/Switzerland) over the past two decades has been characterized by increasing growths of *T. fenestrata*. Eloranta (1974) has noted that sewage discharge to the humus-rich northern part of Lake Keurusselkä of the Finnish Lake District has resulted in high standing crops of *Tabellaria fenestrata*. Szymanski-Bucarey (1974) has also charted changes in phytoplankton composition during eutrophication of the originally oligo-dystrophic Titisee (Germany) and described the phytoplankton as changing from a "*Mallomonas*-*Dinobryon* type" to a "*Fragilaria*-*Anabaena* type", but also with large increases in the previously absent *Tabellaria fenestrata*, as sewage wastes rapidly eutrophied the lake. There is therefore no reason to conclude that the optical properties and dissolved organic matter content of Jerry Lake are inhibiting growth of *T. fenestrata* which is thriving in the less coloured waters of Harp Lake. It is likely that scarcity of available nutrients precludes its growth in Jerry Lake. *T. fenestrata*'s well established niche in the phytoplankton of Harp Lake probably should be interpreted as a sign of incipient eutrophication of the lake, although P concentrations in the lake averaging 11-12 μg/l throughout the ice-free period are still much lower than the 20 μg P/l required for optimum growth of this organism (Soeder *et. al*., 1971).

In European lakes, increased abundance of *Tabellaria fenestrata* is a well known precursor of *Oscillatoria rubescens*, a notorious indicator of eutrophication (Ravera and Vollenweider 1968). *O. rubescens* was not found in Harp or Jerry Lakes and, in fact, has rarely been reported from North America. However, *O. redekei*, which is also confined to eutrophic waters (Lund 1960; Meffert 1971), was the dominant *Oscillatoria* species in Harp Lake, although maximum biomass was only 0.02 mm^3/l. A few cells of *O. redekei* were also found in two samples from Jerry Lake (after an exhaustive search!) but its biomass was insignificant. A smaller unidentified *Oscillatoria* sp. was much more important in Jerry Lake but its maximum biomass (0.04 mm^3/l) was also very low. Other well known indicators of eutrophic waters, the cyanophycean "bloom-formers" such as *Aphanizomenon flos-aquae*, *Anabaena* spp. and *Microcystis* spp. were notably absent from Harp and Jerry Lakes. The chroococcalean forms such as *Aphanothece*, *Chroococcus* and *Merismopedia* spp. were the dominant blue-green algae.

Given the measured total P inputs, water residence times and P retention coefficients of the two lakes, the theoretical P concentration in Harp and Jerry Lakes at spring overturn should be 14 and 15 μg P/l, respectively, according to Dillon and Rigler's (1974) equation: $[P] = \frac{L\,(1-R)}{\bar{z}\,\rho}$. The measured concentrations

were 13 μg/l in Harp Lake and 16 μg/l in Jerry Lake. The very similar predicted and measured total P concentrations of both lakes are in excellent agreement with the very similar early summer maxima of phytoplankton biomass (8.4 and 9.9 mm^3/l in Harp and Jerry Lakes, respectively). However, after the decline of the early summer phytoplankton maxima, an anomaly arises during the mid-summer period when an average phytoplankton biomass of only 1.4 mm^3/l was found in Jerry Lake during July and August, while Harp Lake contained an average of 6.0 mm^3 phytoplankton/l during the same mid-summer period. As pointed out, literature data suggest that mid-summer standing stocks of phytoplankton in Jerry Lake should be much higher in view of the lake's P concentrations averaging about 20 μg/l. Phytoplankton species composition and biomass of Jerry Lake suggest oligotrophy; yet, the species composition and biomass of Harp Lake suggest mesotrophy associated with only 11-12 μg P/l.

These data suggest that either P in Jerry Lake was not the limiting nutrient or that much of the P measured as total P was in a form not utilizable by phytoplankton. Since NO_3^--N and NH_4^+-N were not depleted in Jerry Lake's euphotic zone during the mid-summer period, N was not likely limiting phytoplankton growth. Furthermore, it has been shown many times that P is the element most likely to limit algal growth in Precambrian Shield lakes (Michalski and Conroy 1973; Schindler and Fee 1974; Michalski and Nicholls 1975). The possibility that a nutrient other than P limited phytoplankton growth in Jerry Lake is therefore remote. The high mid-summer total P concentrations and low phytoplankton biomass in Jerry Lake suggest that much of the P may be associated with humic-iron compounds and as such may not be readily available for algal growth (Golterman 1973; Jackson and Schindler 1975).

Although iron concentration in Jerry Lake's inflow were 2-3 times higher during mid-summer than during spring and early summer, colour data from Jerry Lake are not extensive enough to determine whether humic compounds were less important in the lake during spring and early summer when the phytoplankton did grow well and did achieve a high standing stock (9.9 mm /l) at the expense of somewhat lower total P concentrations. However, Secchi disc and phytoplankton data suggest that the lake did become more coloured through the ice-free period. The poor transparency associated with high phytoplankton biomass in early summer improved initially as the phytoplankton maximum declined, but the rather poor Secchi disc readings associated with low phytoplankton density during late summer and fall can most likely be attributed to an increase in humic matter, which in turn suggests that the formation of humic-iron complexes bonding P in a form unavailable to algae may have limited phytoplankton growth during the middle and latter part of the ice-free period.

Since many of the lakes in Ontario's Precambrian Shield are brown-water ("humic") lakes, it is possible that much of the total P loading to them from natural land drainage is of no direct consequence to algal production. It may be of use to develop a simple algal assay procedure for stream waters of the Shield which would determine the relative proportions of "utilizable" and "non-utilizable" total P. Such a correction of total P loading data should make Dillon and Rigler's (1975) model more readily applicable to humic lakes.

Zooplankton

Historically, limnological investigations have included crustaceans and rotifers in zooplankton studies but surprisingly little attention has been given to ciliates. However, Elorenta (1973) found ciliates to be the most important component of the zooplankton (as biomass) during the winter in Finland's Lake Keurusselkä. Although the zooplankton of Harp and Jerry Lakes was not sampled routinely, Ciliophora were counted during phytoplankton enumerations. As well, analyses of the Lugol's iodine preserved portions of the sedimentation traps provided some comparative qualitative data for each lake.

Ciliophora from Harp and Jerry Lakes were not identified to genus, but total densities of the organisms were similar in both lakes throughout most of the annual period. The euphotic zones of both lakes were characterized by early summer peaks in numbers of ciliates (Fig. 30) but with the maximum in Jerry Lake preceding the maximum in Harp Lake by one sampling interval (3 weeks). It is noteworthy that the early summer phytoplankton biomass peaks accompanied the Ciliophora peaks and were similarly out of phase in the two lakes. After the crashes of the early summer pulses, no other relationships between ciliate densities and phytoplankton are obvious through the remainder of the annual period. It is doubtful if differences in ciliate density between the two lakes are great enough to lead to any conclusions relative to differences in trophic state.

Owing to the small numbers of organisms in the subsamples from the preserved sedimentation traps and the lack of exposure of the traps during the early summer period, the taxonomic composition of the crustacean zooplankton of both Harp and Jerry Lakes is undoubtedly more diverse than Table 9 indicates. Nevertheless, comparisons are possible because periods of exposure

Table 9. Some crustacean zooplankters from Harp and Jerry Lakes collected in sedimentation traps. Key is as follows: common, ++; present, +; rare or absent, –.

	Harp Lake	Jerry Lake
Diaptomus minutus	++	+
Diaptomus sicilis	+	-
Diaptomus oregonensis	+	-
Senecella calanoides	++	-
Epischura lacustris	-	+
Cyclops bicuspidatus thomasii	++	++
Cyclops vernalis	++	++
Tropocyclops prasinus mexicanus	+	++
Bosmina longirostris	+	-
Chydorus sphaericus	+	-
Daphnia galeata mendotae	-	+
Mysis relicta	+	+
Pontoporeia affinis	+	+

of the traps in both lakes during mid-summer, late summer, autumn and late winter were coincident.

The most common zooplankter in Harp Lake was the copepod *Diaptomus minutus* which was also abundant in Jerry Lake during the late winter but was dominated overall by *Cyclops bicuspidatus thomasii*. Next in order of dominance in Harp Lake were *C. b.thomasii*, *Cyclops vernalis* and *Senecella calanoides*. Second and third most dominant taxa in Jerry Lake were *C. vernalis* and *D. minutus*.

The rather crude method of investigating zooplankton (subsampling sedimentation traps) probably has precluded any extensive interpretation of the data. However, it is important to note that the glacial relict *Mysis relicta* (opossum shrimp) is present in both Harp and Jerry Lakes. The preferred habitat of the species (cold hypolimnia of deep lakes) may be somewhat less desirable in Jerry Lake, where by October, the dissolved oxygen concentration of most of the hypolimnion was less than 1.5 mg/l. In view of its preference for the lake bottom and near-bottom waters (Carpenter et al., 1974), the vertical distribution of *M. relicta* may be atypical in both Harp and Jerry Lakes during those periods of the year when dissolved oxygen in the bottom waters is depleted and the organism seeks water of higher oxygen content.

It is noteworthy that *M. relicta* and *Pontoporia affinis* (an amphipod, also present in both lakes and with similar habitat preferences) are very important fish food organisms and their existence may be threatened if dissolved oxygen depletion, especially in Jerry Lake, becomes more severe.

The dominant zooplankters of Jerry Lake were cyclopoid copepods and because of their predacious relationships with rotifers and small crustaceans and their lack of direct dependence on primary producers, they are not useful as trophic status indicators. On the other hand, the presence in Harp Lake of both *Diaptomus sicilis* and *Bosmina longirostris*, very successful oligotrophic and eutrophic species, respectively (McNaught et. al., 1975) suggests that Harp Lake is in a stage of transition from oligotrophy to eutrophy. Further supporting evidence relates to the domination of Harp Lake zooplankton by *Diaptomus minutus*, a form most common to mesotrophic waters (McNaught et. al., 1975).

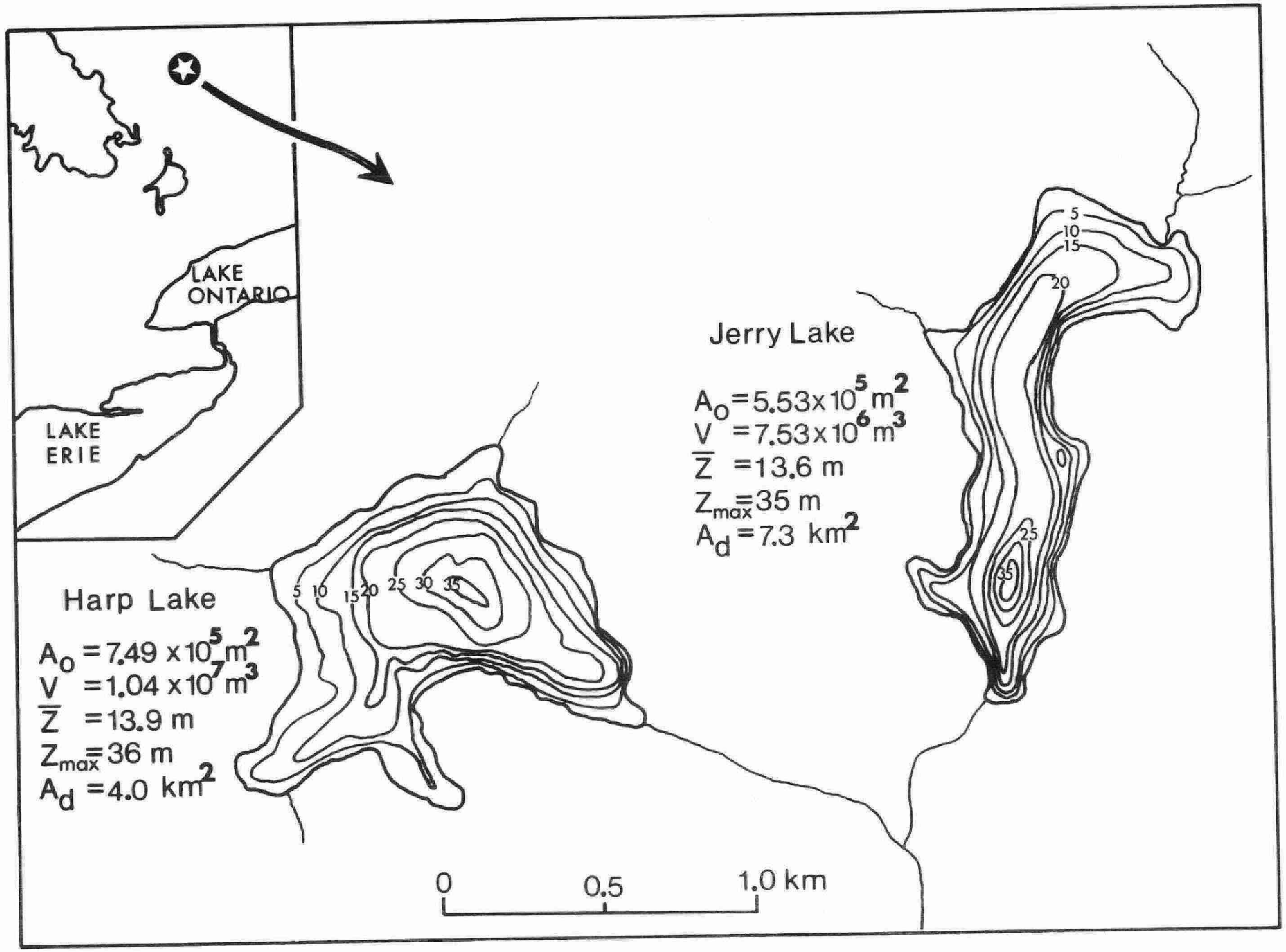

FIG. 1. Morphometric data for Harp and Jerry Lakes keyed as follows: A_o, lake area; V, lake volume; $\bar{z}$, mean depth; Z_{max}, maximum depth; A_d, land area of catchment.

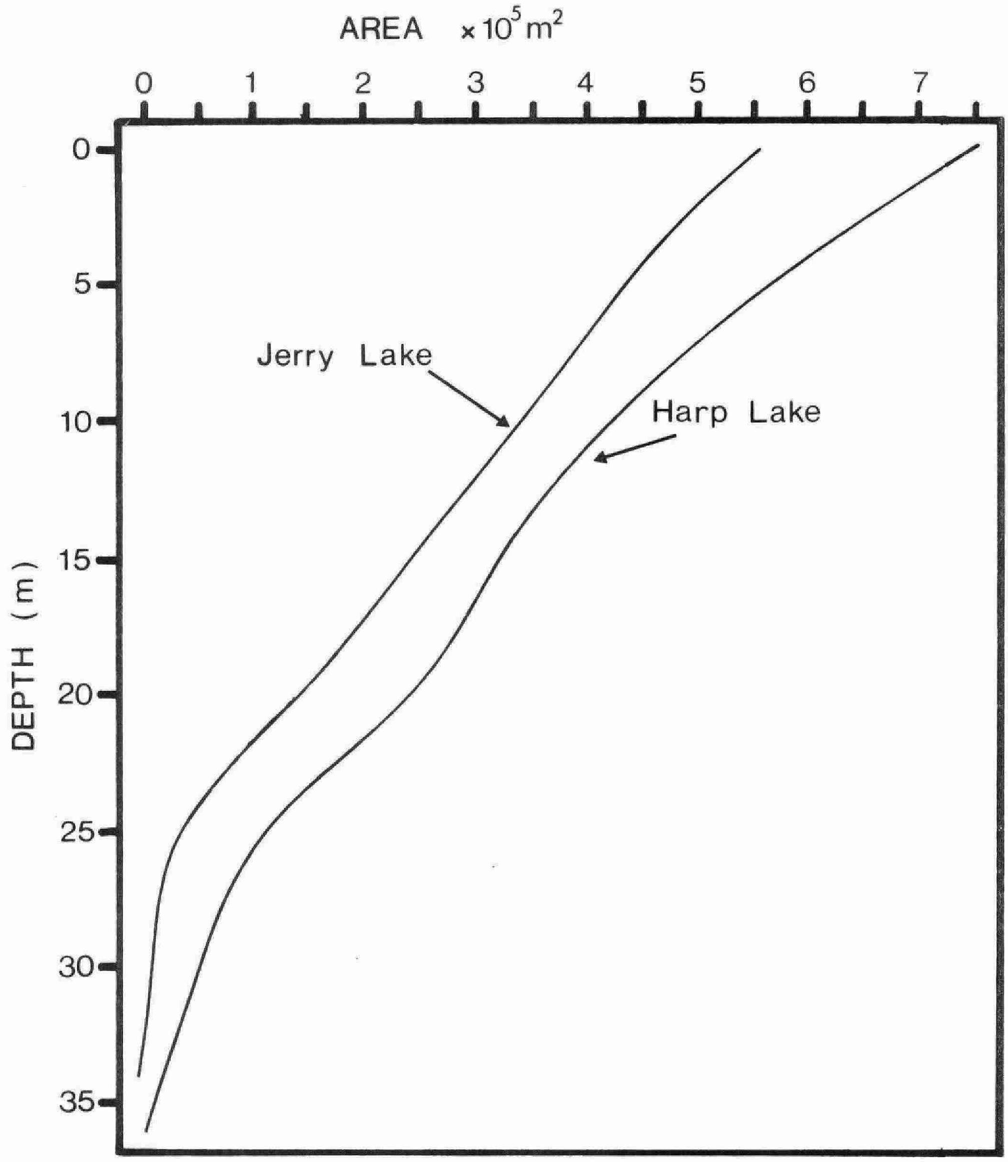

FIG. 2. Hypsographs of Harp and Jerry Lakes.

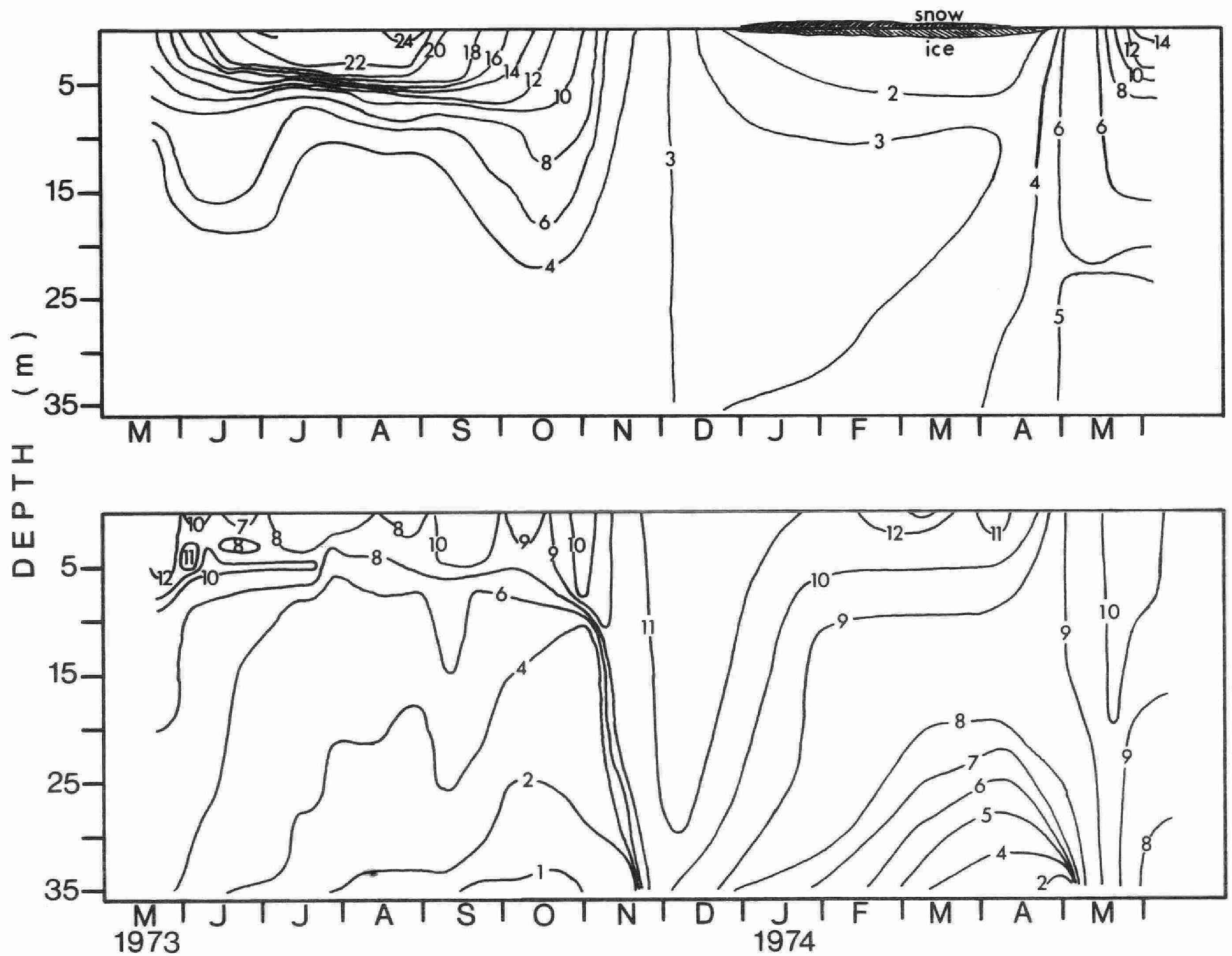

FIG. 3. Vertical distribution of (a) water temperatures (Celsius) and (b) dissolved oxygen (mg/l) in Harp Lake between May of 1973 and June of 1974.

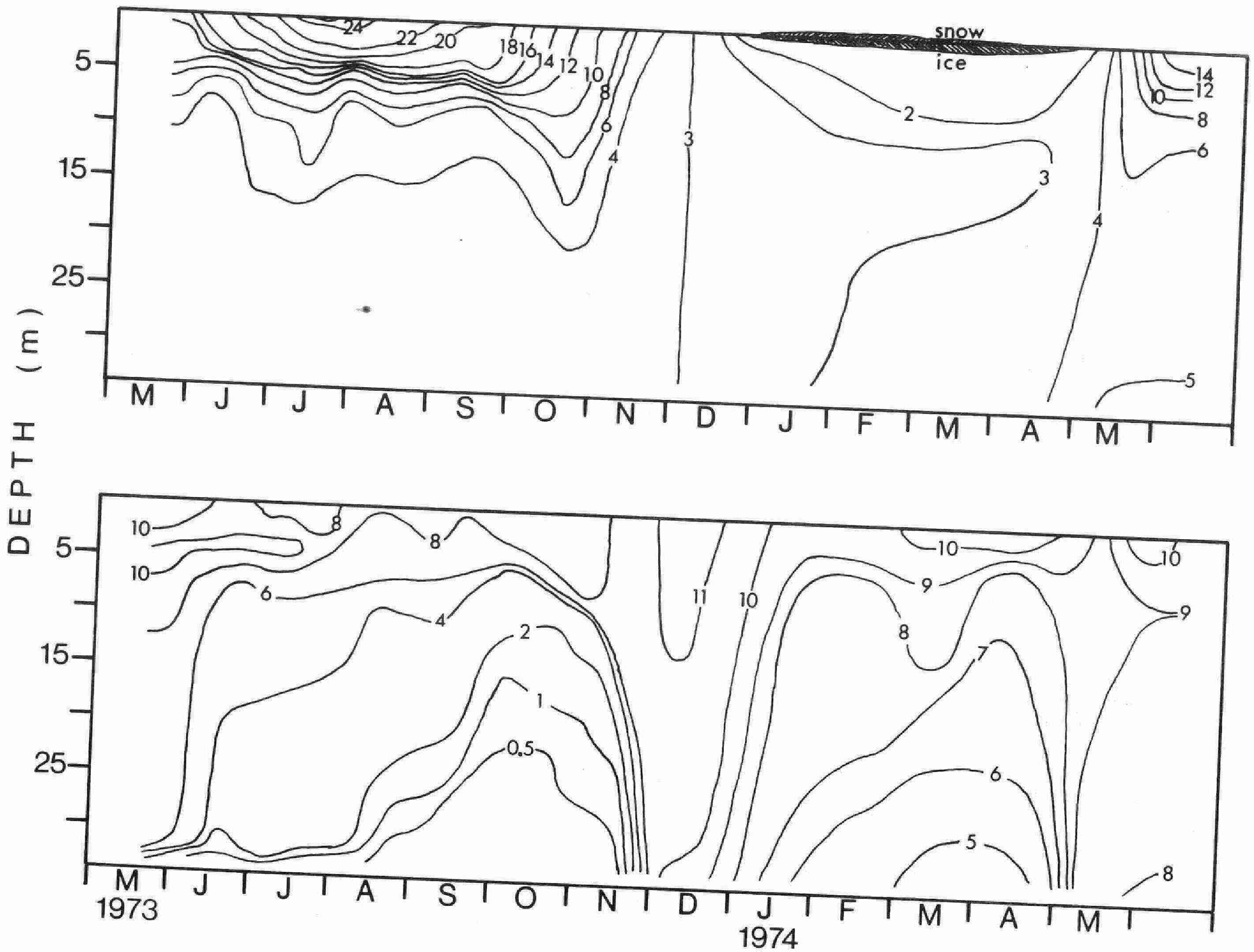

FIG. 4. Vertical distribution of (a) water temperatures (Celsius) and (b) dissolved oxygen (mg/l) in Jerry Lake between May of 1973 and June of 1974.

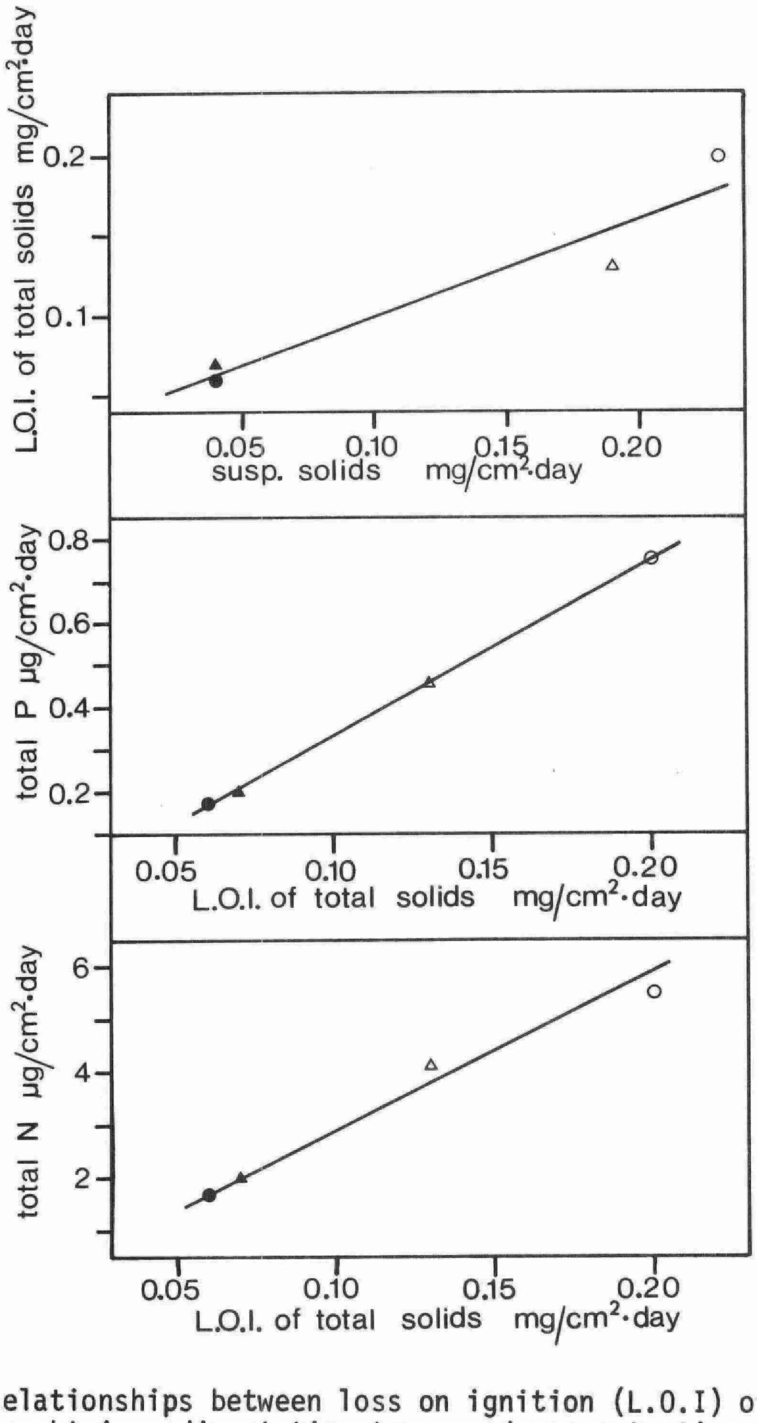

FIG. 5. Relationships between loss on ignition (L.O.I) of total solids caught in sedimentation traps and concentrations of suspended solids, total N and total P expressed as sedimentation rates. Keyed as follows: Harp Lake: ice-free (Δ), ice covered (▲); Jerry Lake: ice-free (o), ice covered (●).

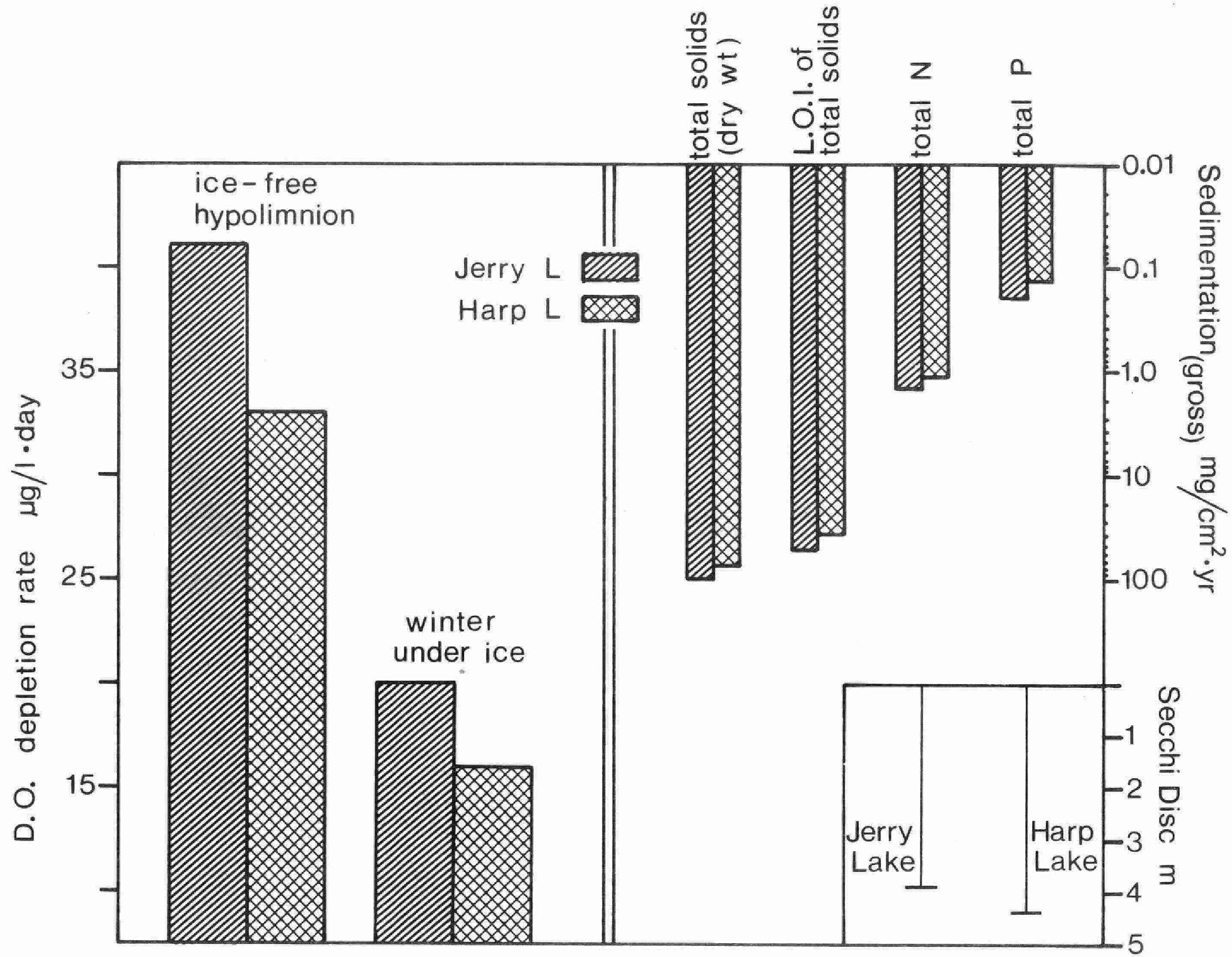

FIG. 6. Dissolved oxygen depletion rates in Harp and Jerry Lakes under winter ice cover and in the hypolimnia during the summer stagnation period. Also illustrated for both lakes are average ice-free period Secchi disc readings as well as total annual sedimentation (into traps suspended at 1 m above lake bottom) of total P, total N, organic weight (L.O.I. of total solids) and of total solids.

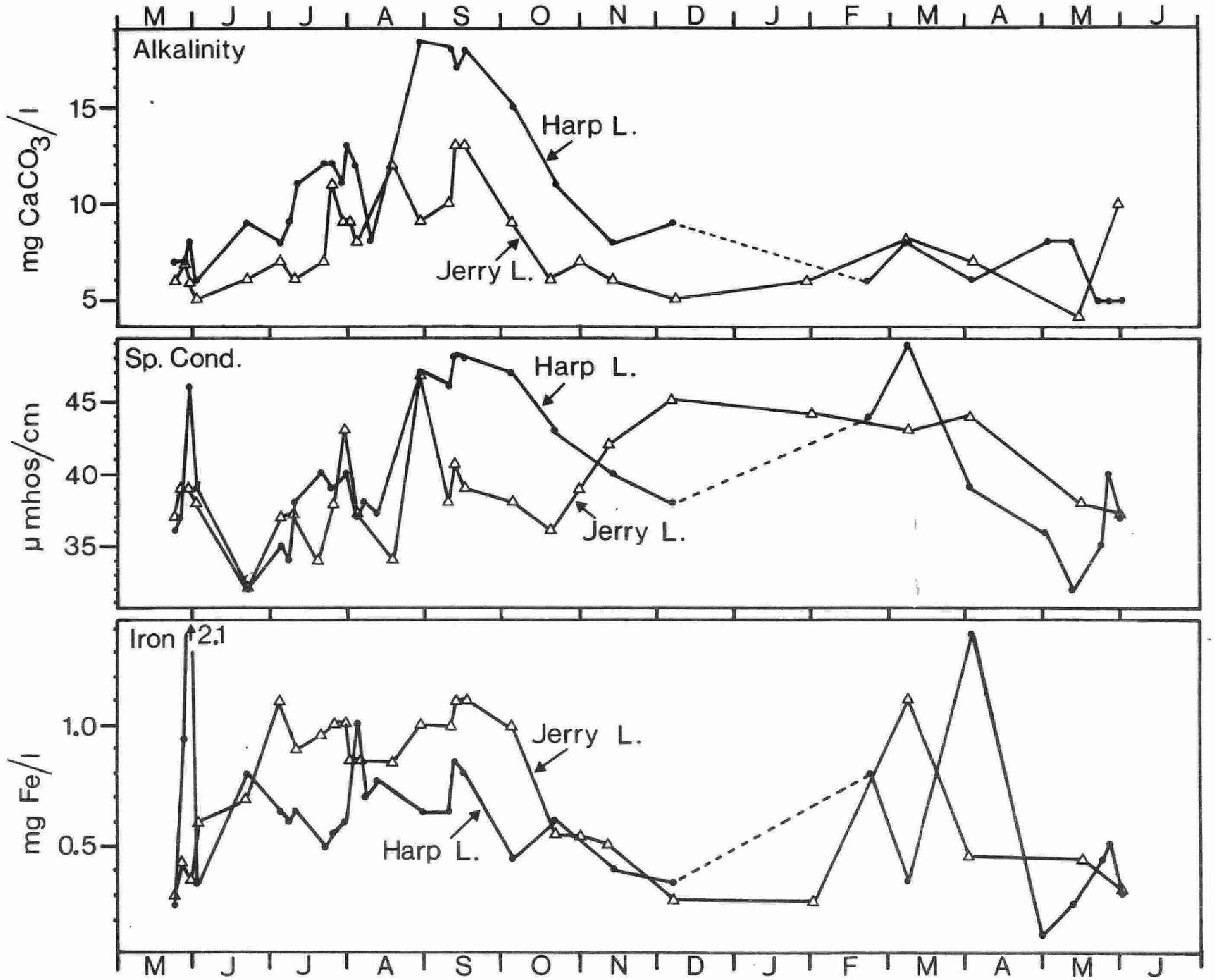

FIG. 7. Some mineral characteristics (alkalinity, specific conductance and total iron) of the inflow streams to Harp and Jerry Lakes between May of 1973 and June of 1974.

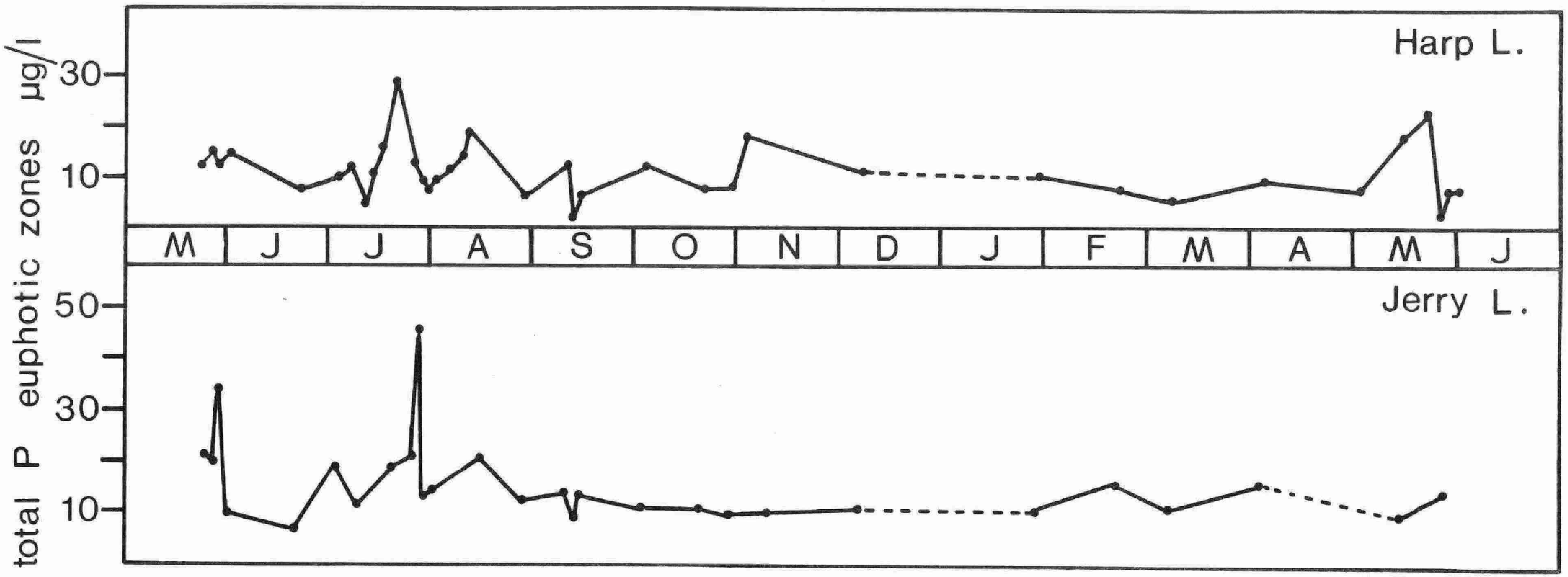

FIG. 8. Concentrations of total phosphorus in the euphotic zones of Harp and Jerry Lakes between May of 1973 and June of 1974.

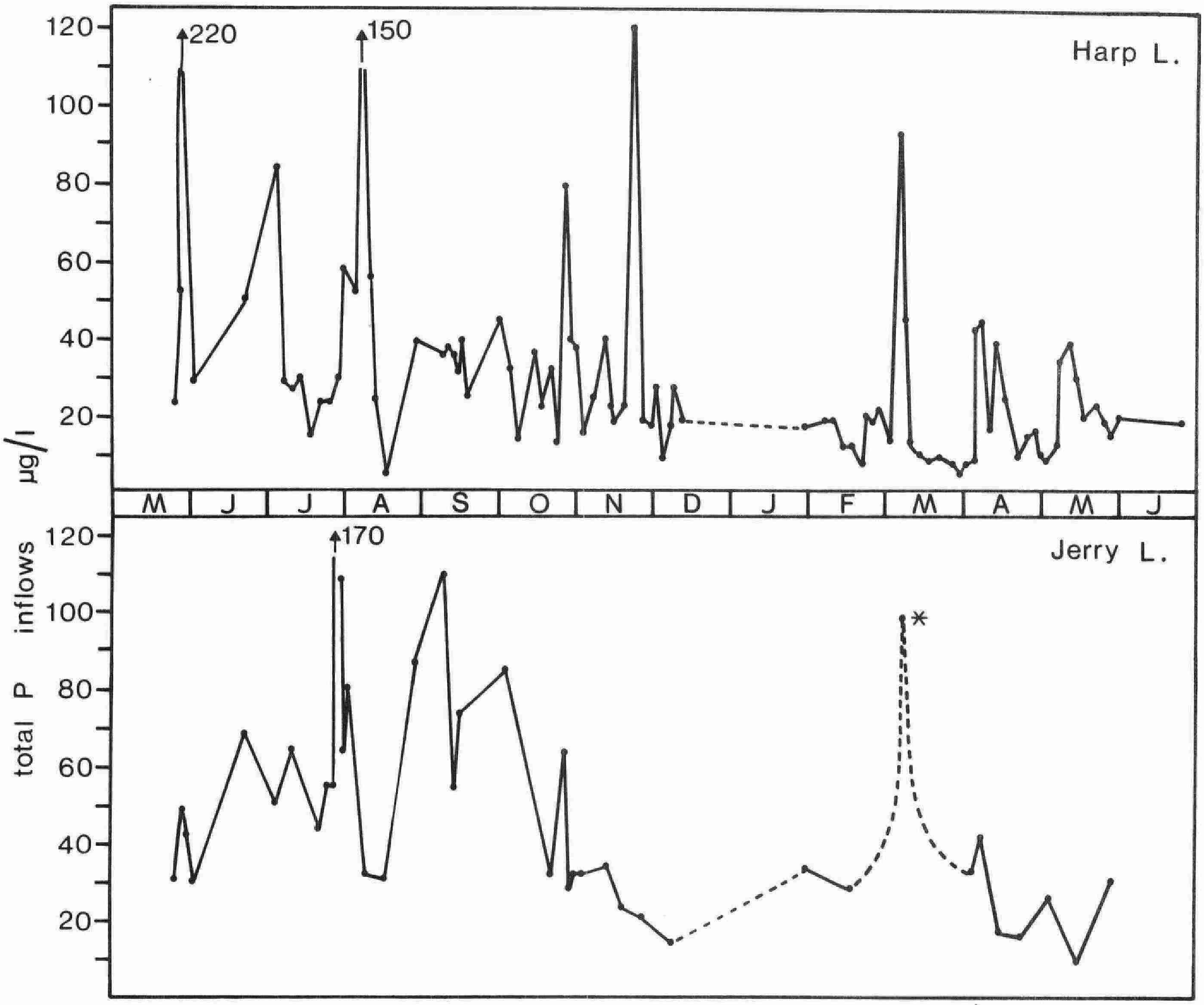

FIG. 9. Concentrations of total phosphorus in the inflowing streams of Harp and Jerry Lakes between May of 1973 and June of 1974. It was assumed that the peak* in P concentration on March 7 in Jerry Lake's inflow was of much shorter duration than would be inferred from straight line interpolation between sampling dates in February, March and April (see P concentration peak in Harp Lake inflow, Fig. 9). Hyperbolic interpolation between the three sampling dates was an attempt to decrease probable error in P loading calculations.

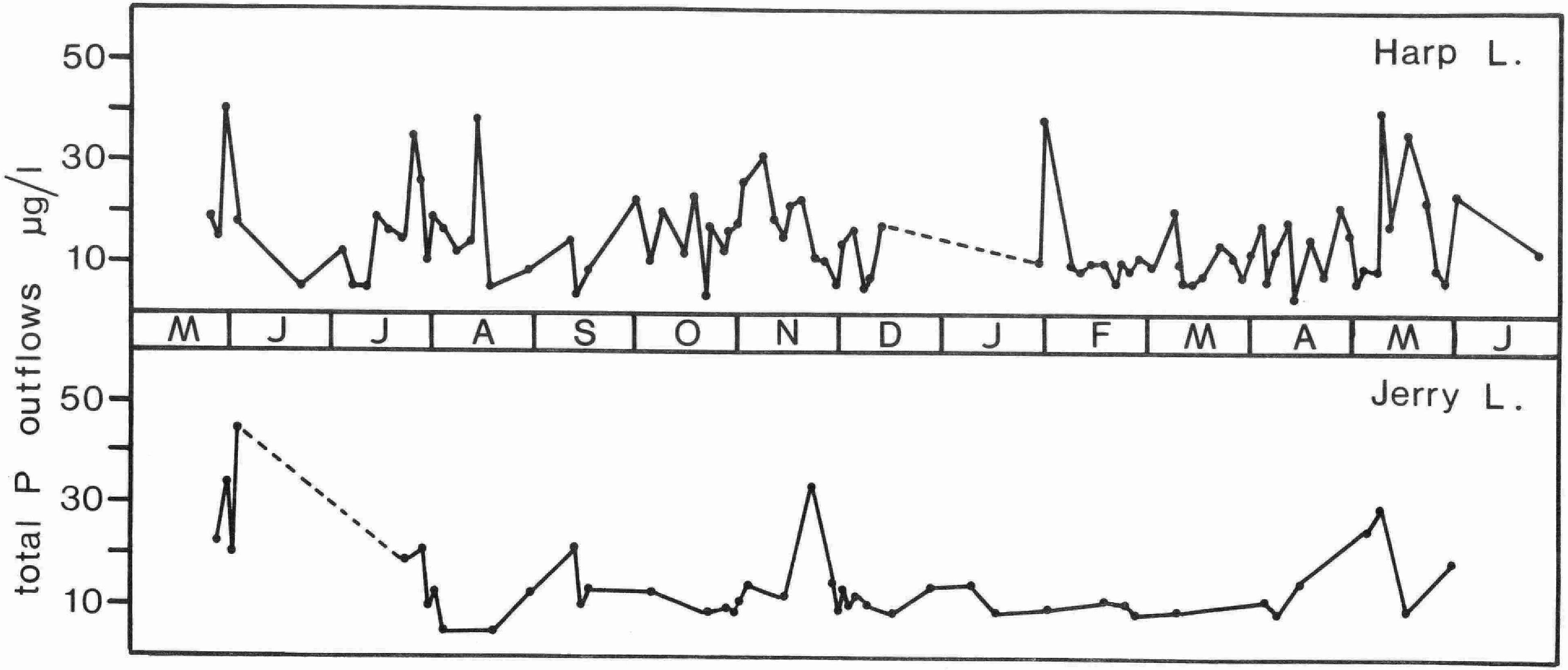

FIG. 10. Concentrations of total phosphorus in the outflows of Harp and Jerry Lakes between May of 1973 and June of 1974.

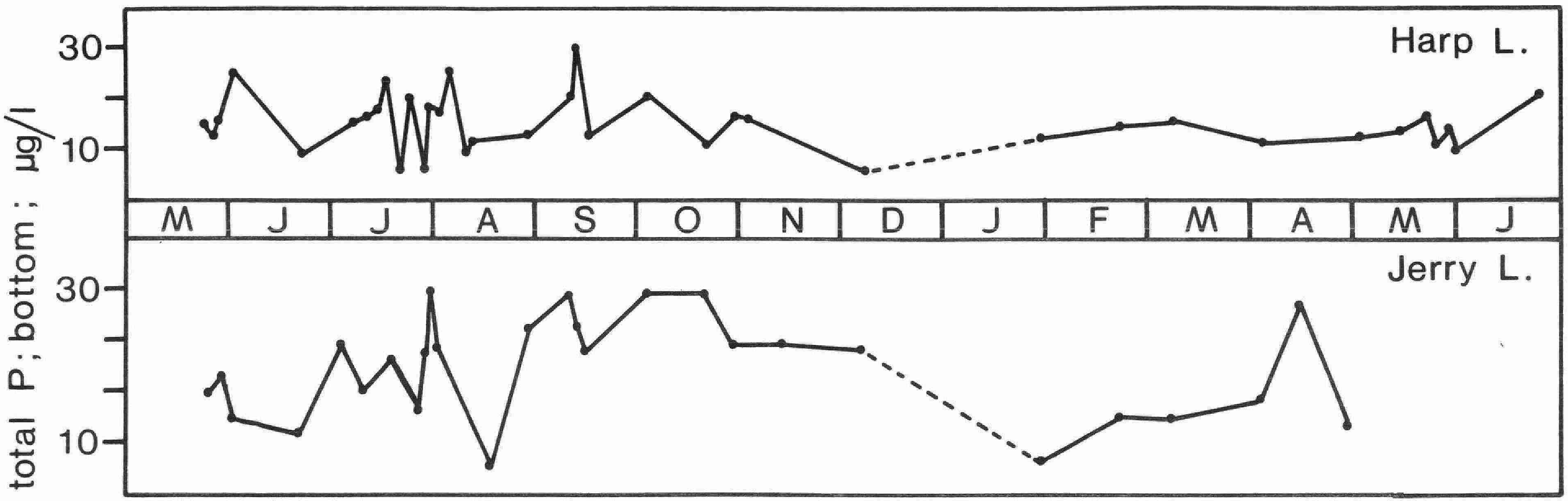

FIG. 11. Concentrations of total phosphorus at 1 m above lake bottom in Harp and Jerry Lakes between May of 1973 and June of 1974.

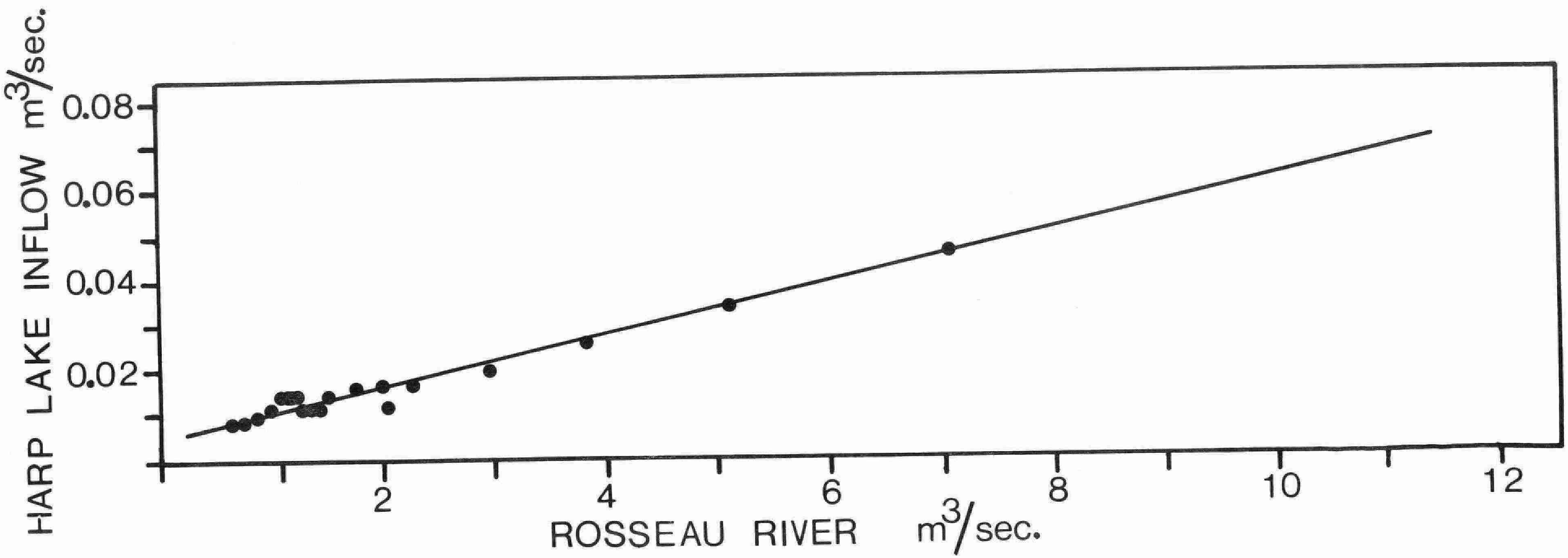

FIG. 12. Relationship between daily measurements of the Harp Lake inflow and the nearby, much larger Rosseau River between May 16 and June 6, 1974 following a peak in the Rosseau River hydrograph. The plotted points are out of phase by one day to allow for the slower response time of the larger river.

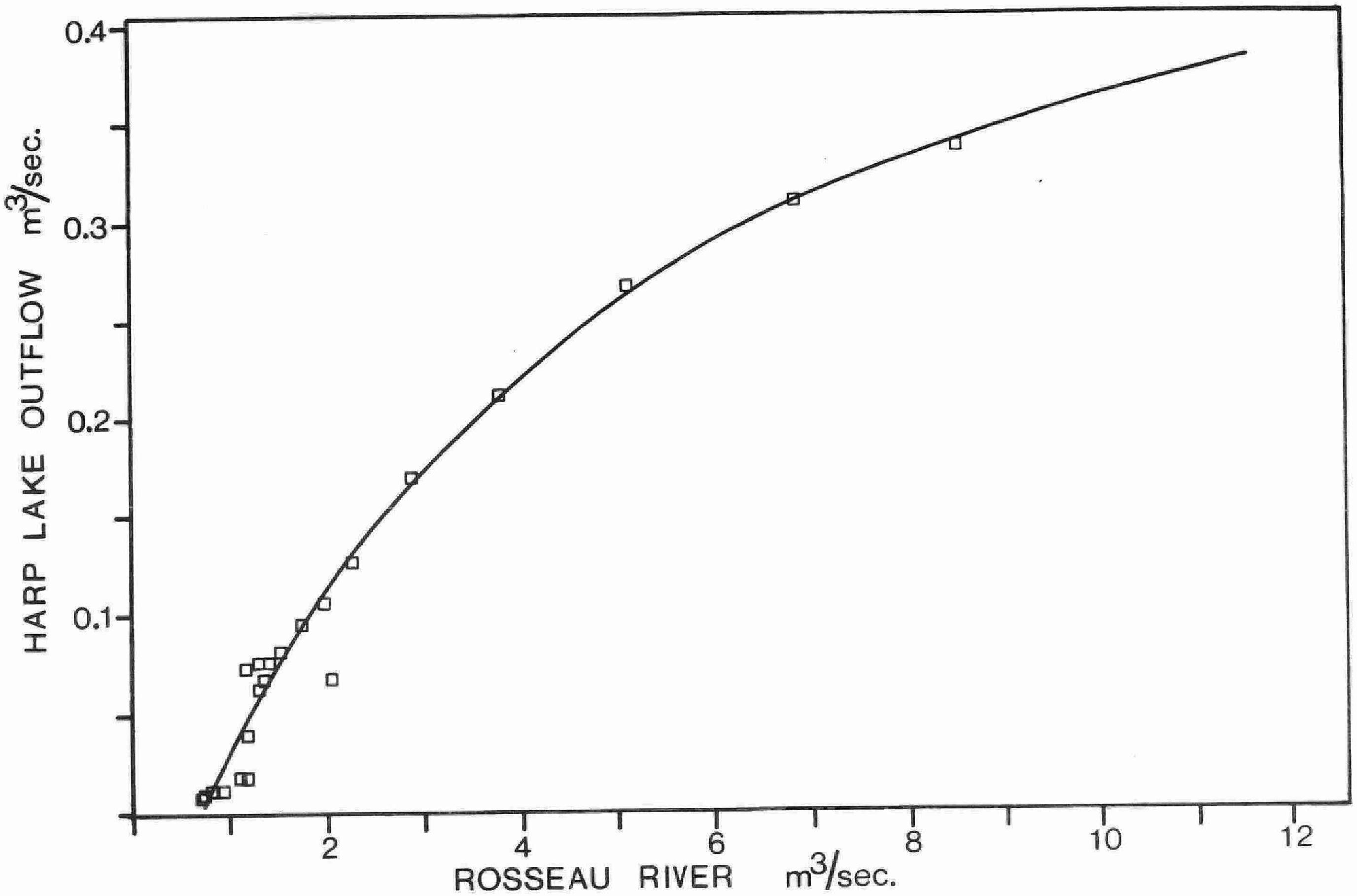

FIG. 13. Relationship between daily measurements of the Harp Lake outflow and the nearby, much larger Rosseau River between May 16 and June 6, 1974 following a peak in the Rosseau River hydrograph.

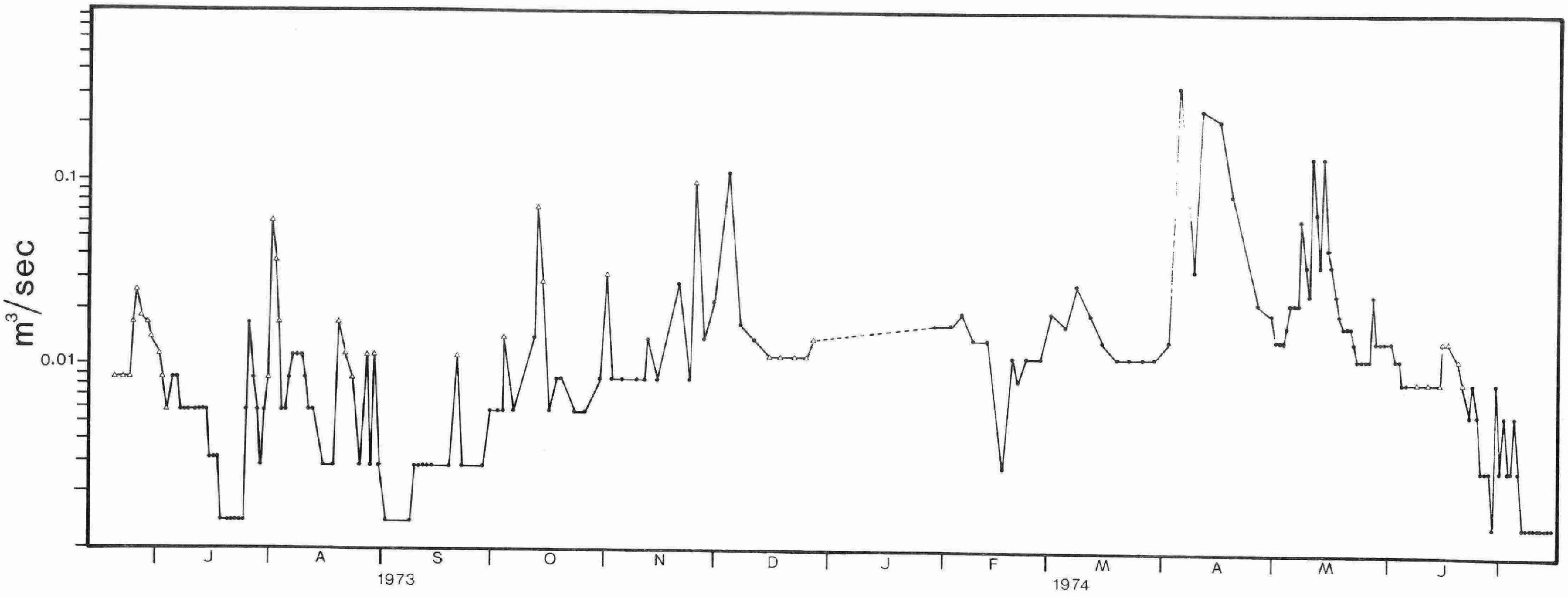

FIG. 14. Hydrograph of Harp Lake's major inflow between May of 1973 and July of 1974. Closed circles represent measured values and open triangles represent values determined from Fig.12.

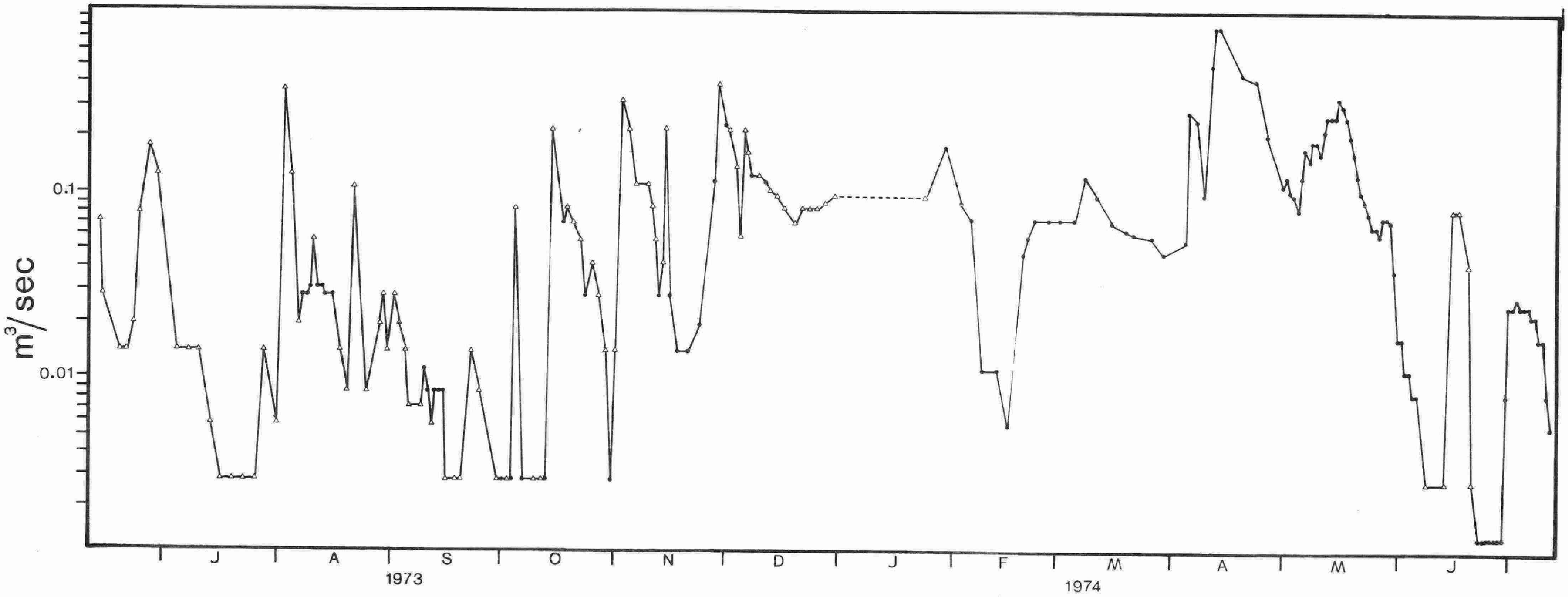

FIG. 15. Hydrograph of Harp Lake's outflow between May of 1973 and July of 1974. Closed circles represent measured values and open triangles represent values determined from Fig. 13.

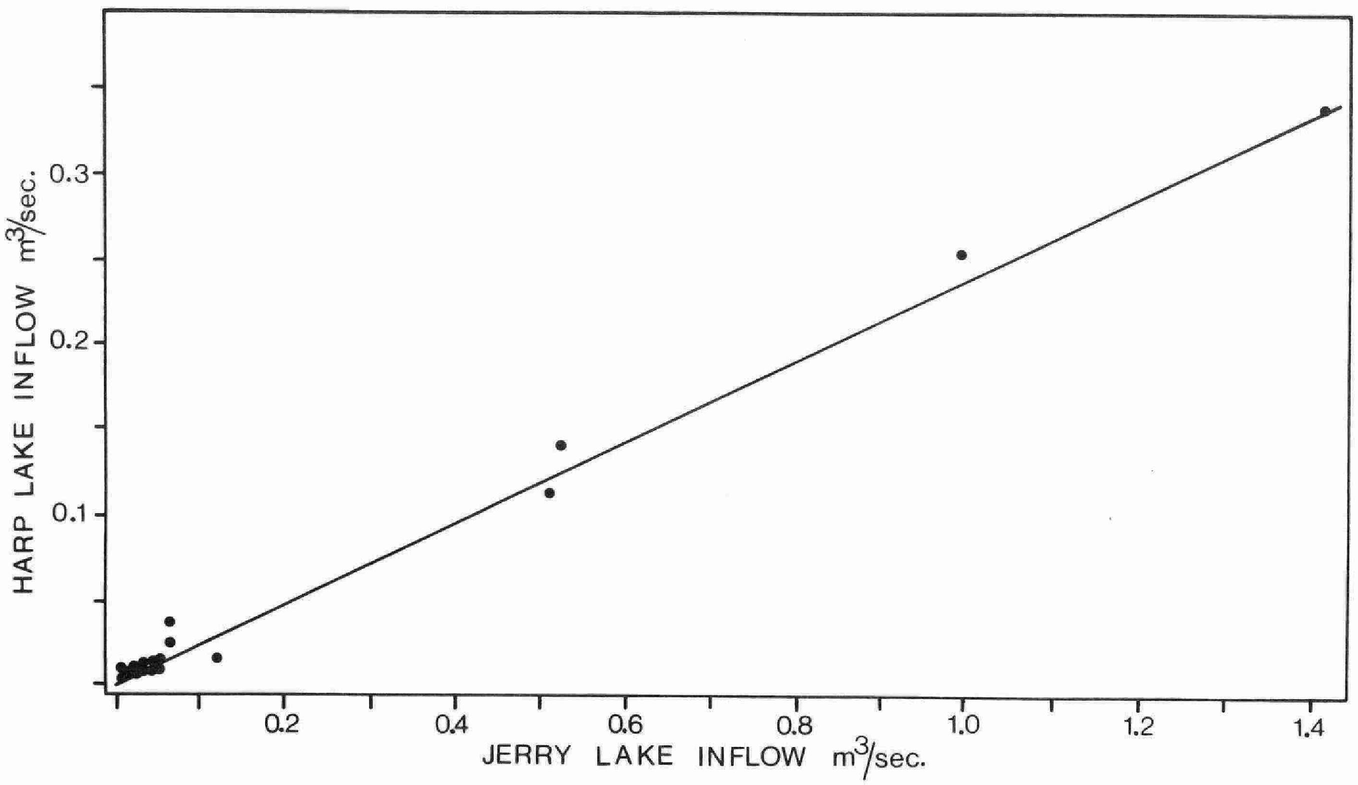

FIG. 16. Relationship between concurrent measurements of Harp and Jerry Lakes' inflows between July of 1973 and July of 1974.

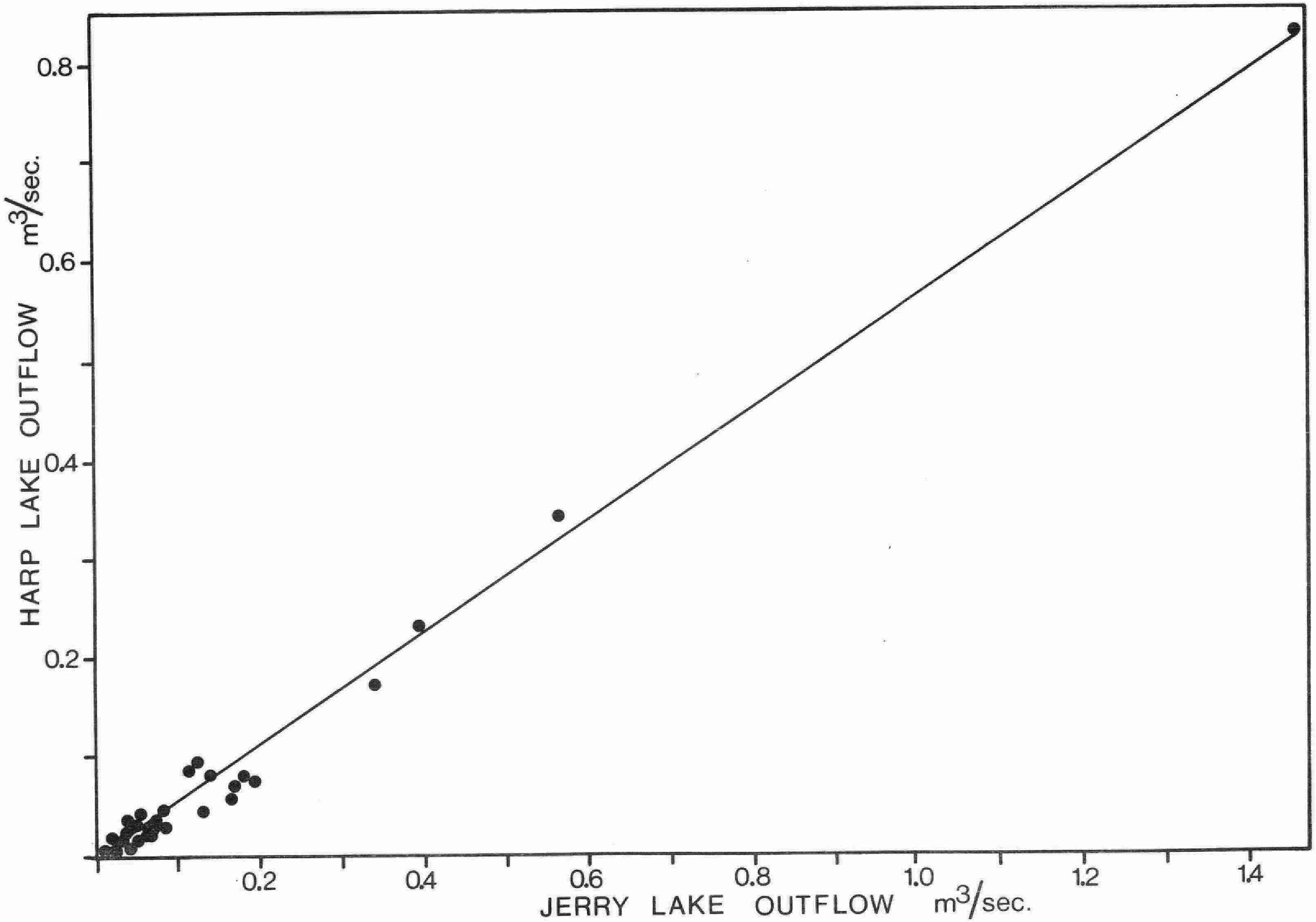

FIG. 17. Relationship between concurrent measurements of Harp and Jerry Lakes' outflows between August of 1973 and July of 1974.

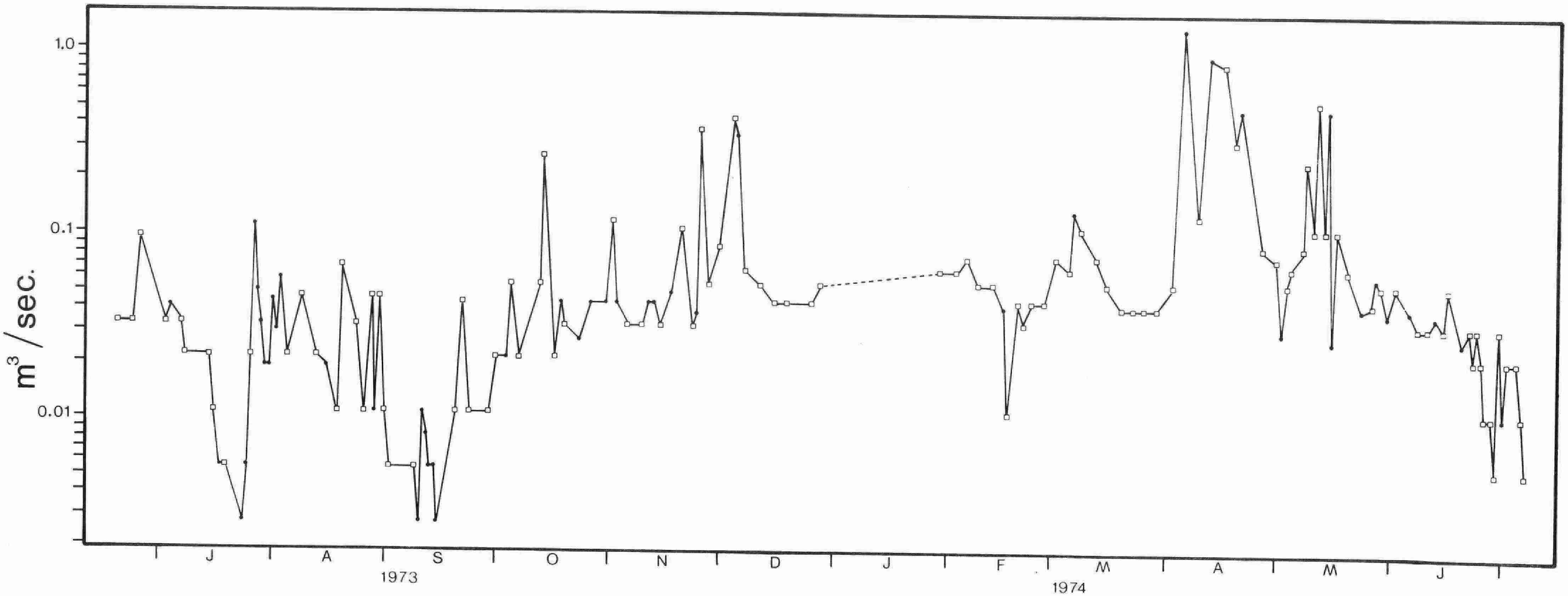

FIG. 18. Hydrograph of Jerry Lake's major inflow between May of 1973 and July of 1974. Closed circles represent measured values and open squares represent values determined from Fig. 16.

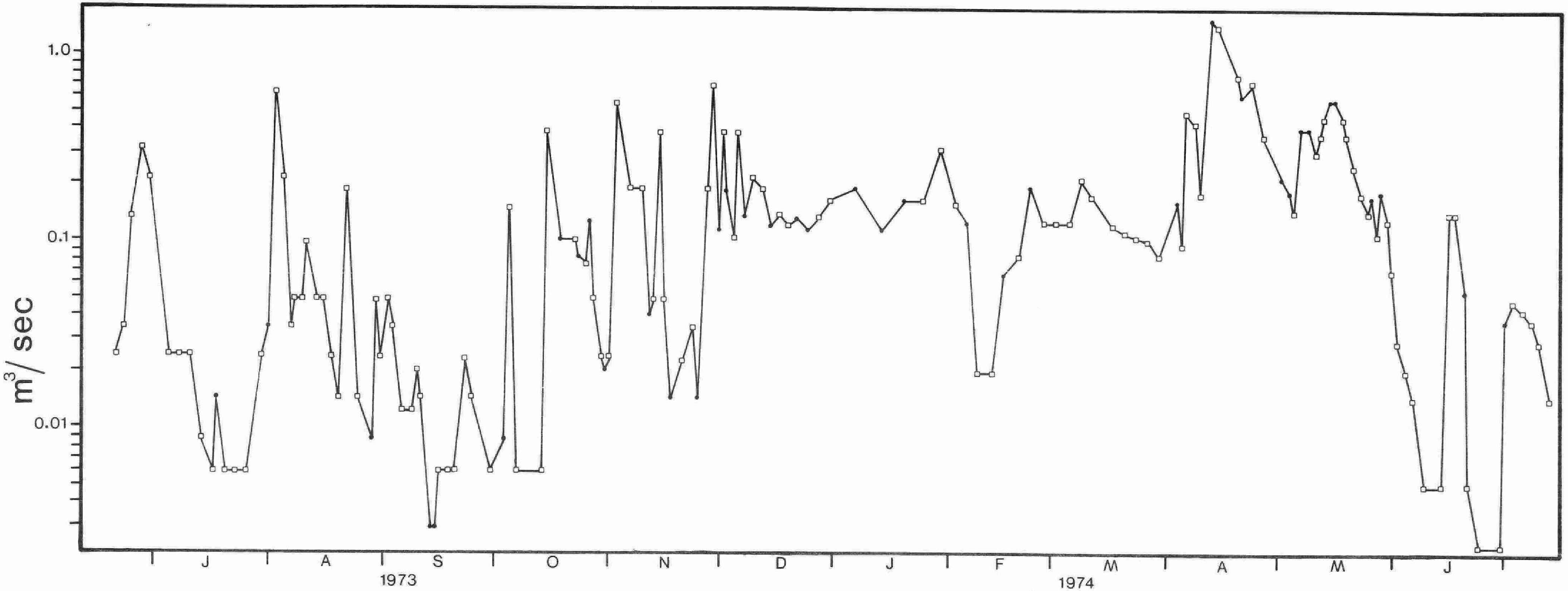

FIG. 19. Hydrographs of Jerry Lake's outflow between May of 1973 and July of 1974. Closed circles represent measured values and open squares represent values determined from Fig. 17.

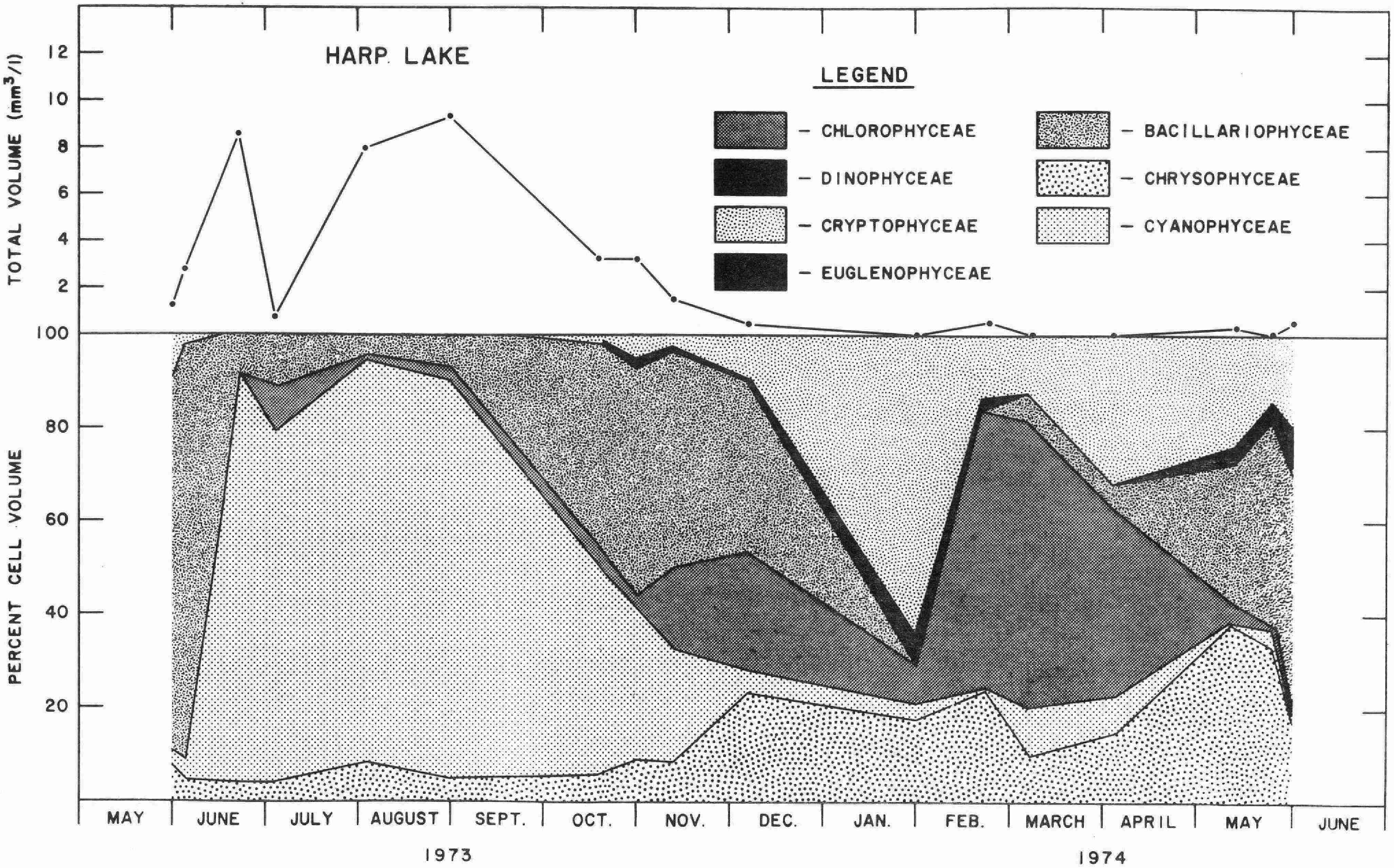

FIG. 20. Seasonal distribution of total biomass (mm^3/l) of total phytoplankton and percentage composition by the dominant classes in the euphotic zone of Harp Lake.

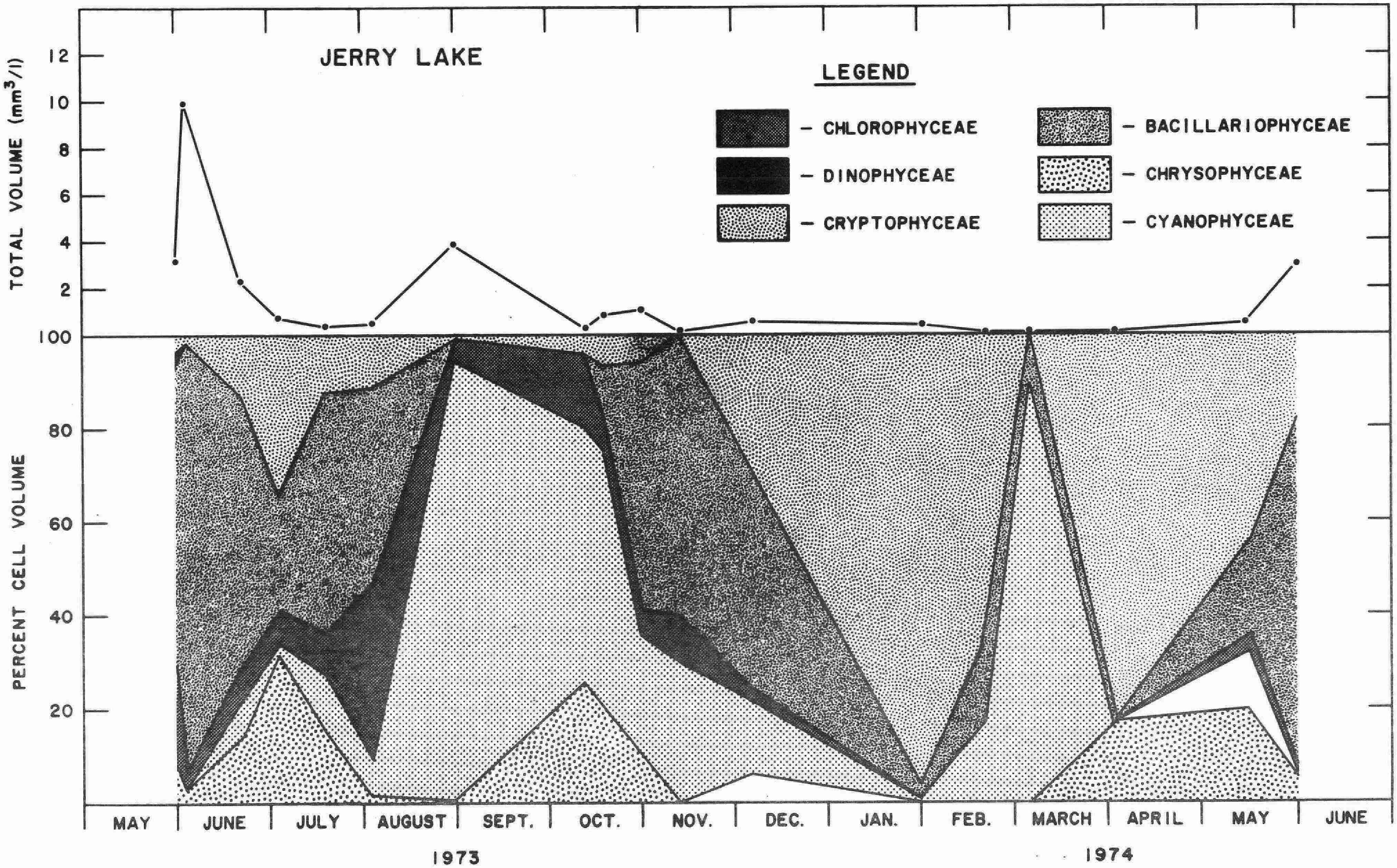

FIG. 21. Seasonal distribution of total biomass (mm^3/l) of total phytoplankton and percentage composition by the dominant classes in the euphotic zone of Jerry Lake.

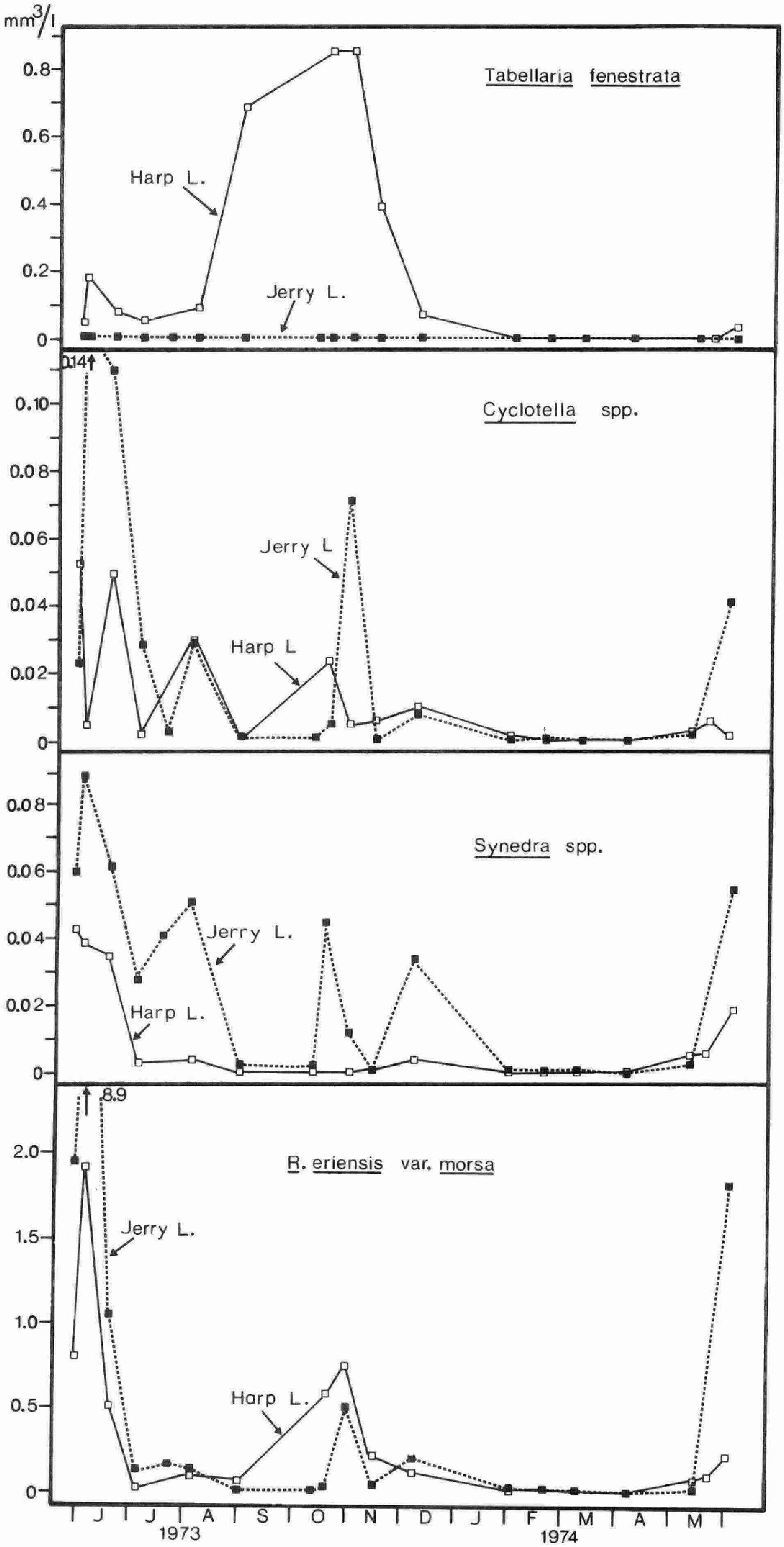

FIG. 22. Seasonal biomass (mm^3/l) of important diatoms (Tabellaria fenestrata, Cyclotella spp., Synedra spp., Rhizosolenia eriensis var. morsa) in Harp and Jerry Lakes between May of 1973 and June of 1974.

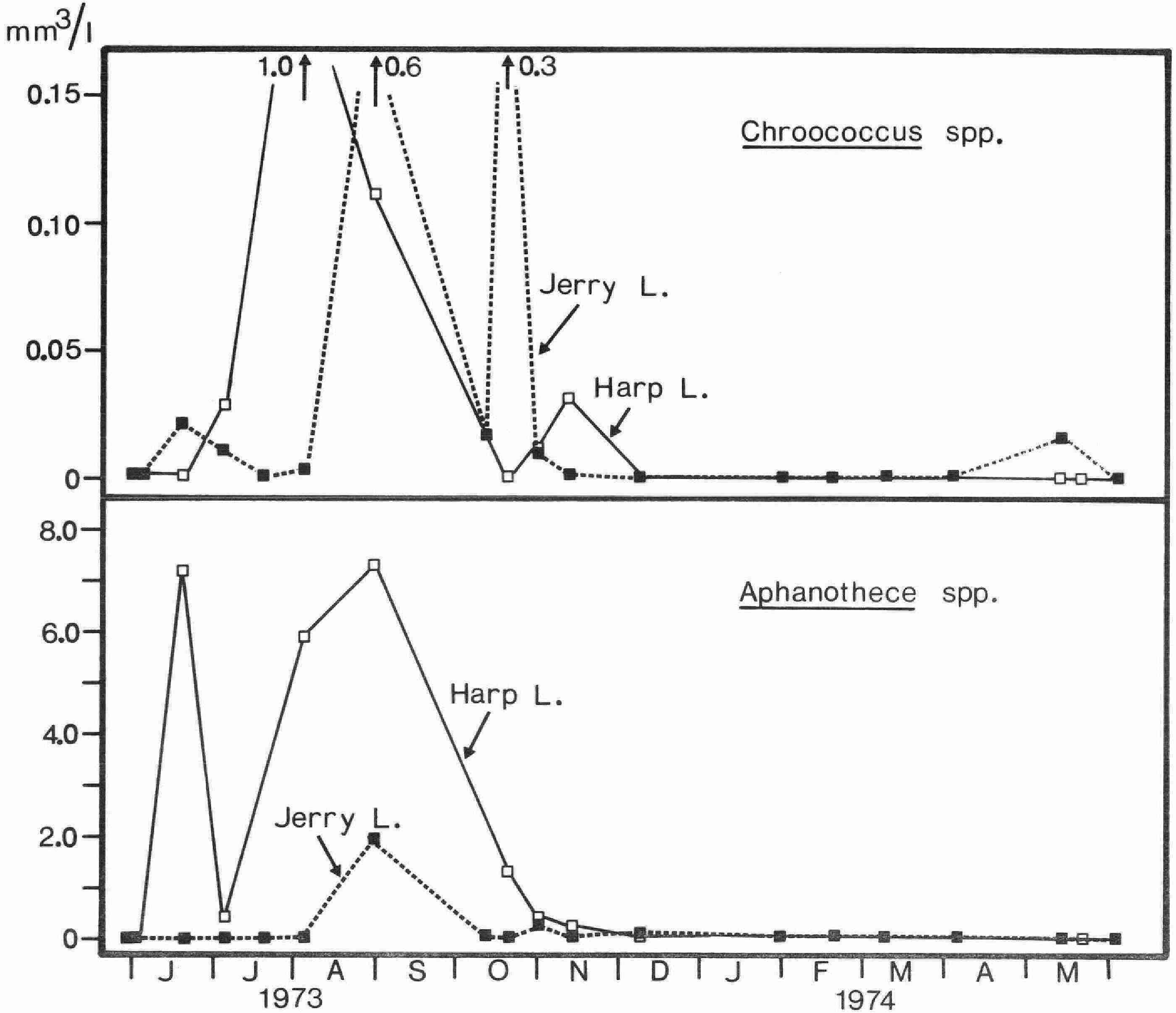

FIG. 23. Seasonal biomass (mm^3/l) of important blue-green algae (<u>Chroococcus</u> spp. and <u>Aphanothece</u> spp.) in Harp and Jerry Lakes between May of 1973 and June of 1974.

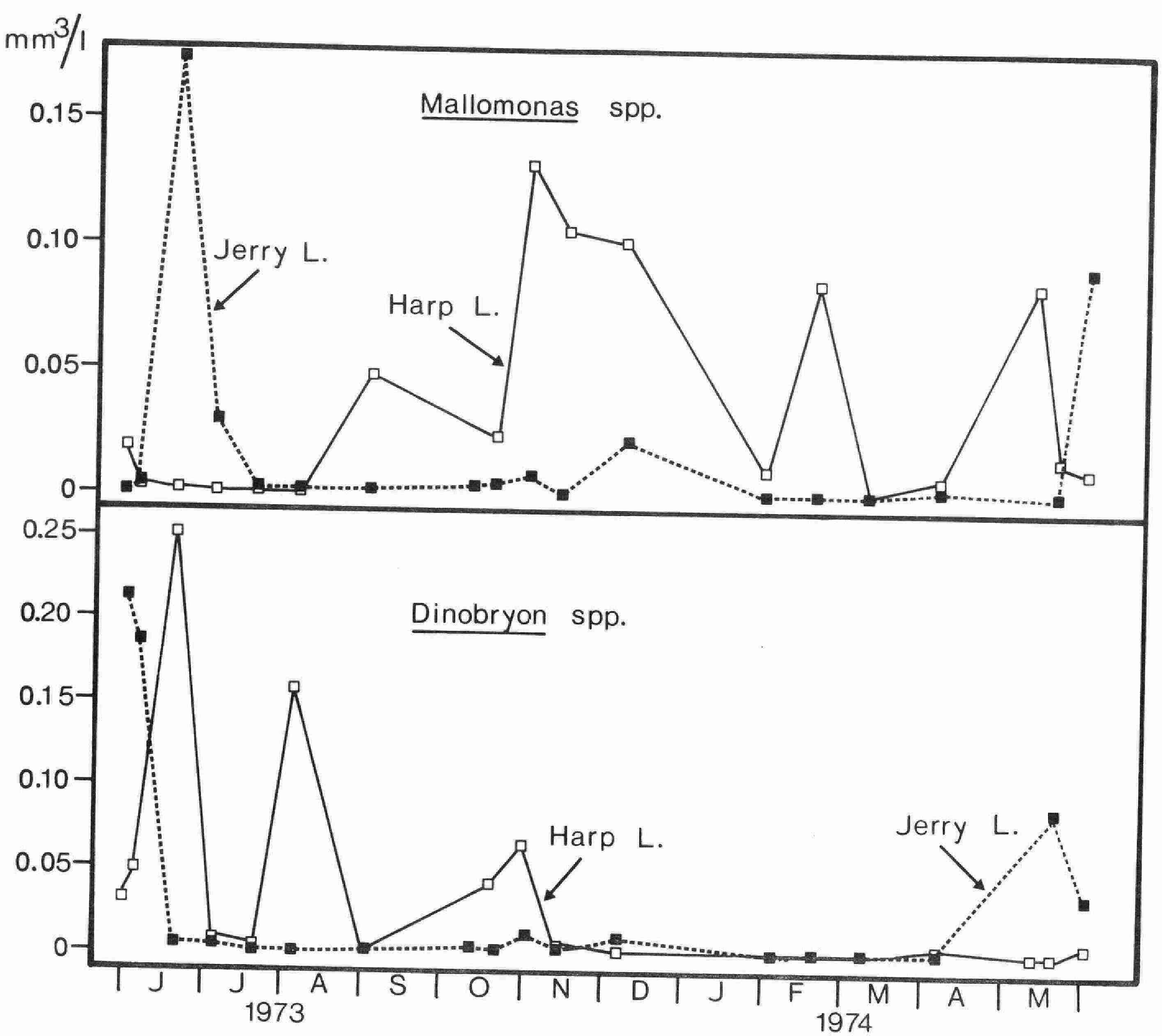

FIG. 24. Seasonal biomass (mm³/l) of important chrysophyceans (*Mallomonas* spp. and *Dinobryon* spp.) in Harp and Jerry Lakes between May of 1973 and June of 1974.

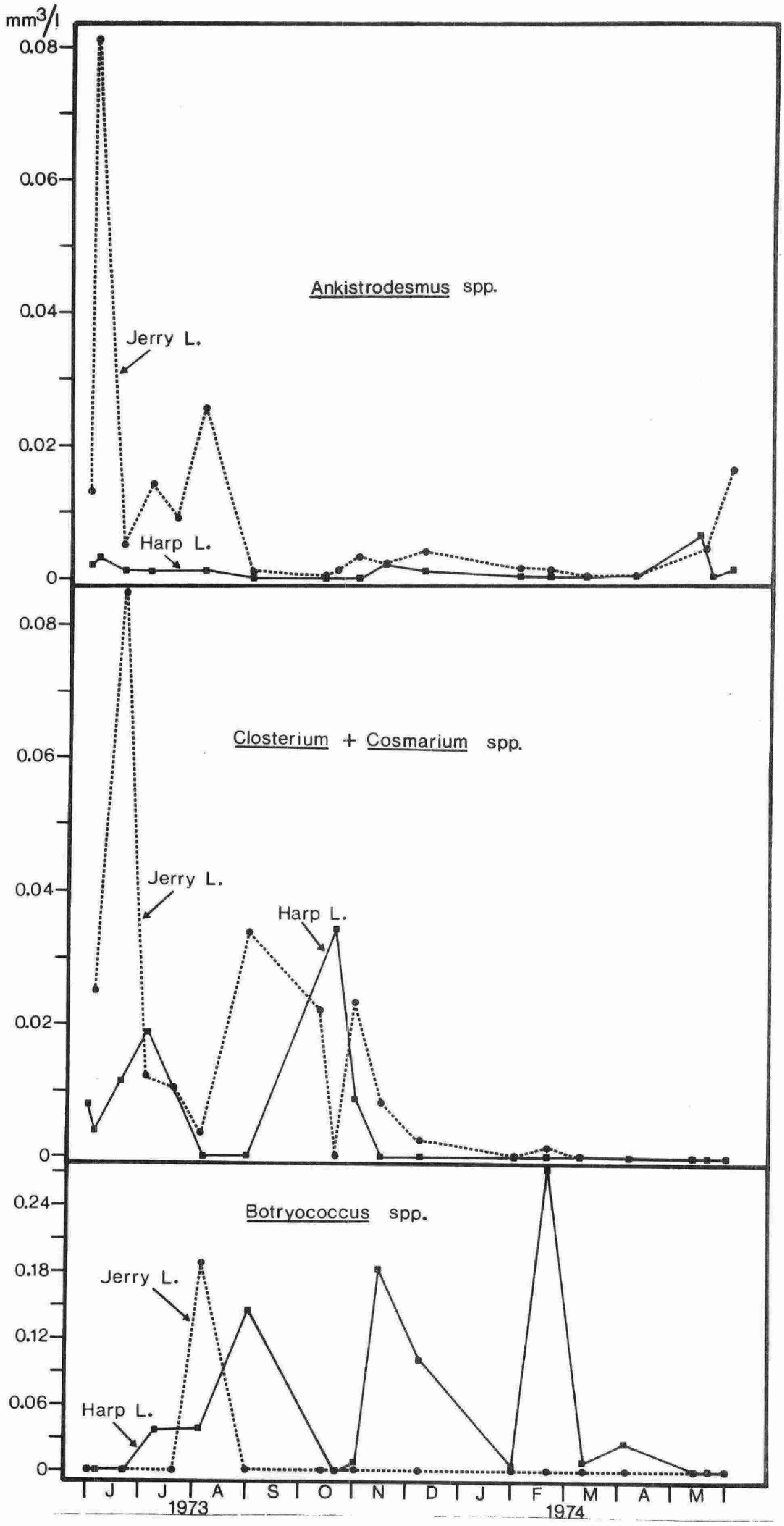

FIG. 25. Seasonal biomass (mm³/l) of important green algae (Ankistrodesmus spp., Closterium and Cosmarium spp. and Botryococcus spp.) in Harp and Jerry Lakes between May of 1973 and June of 1974.

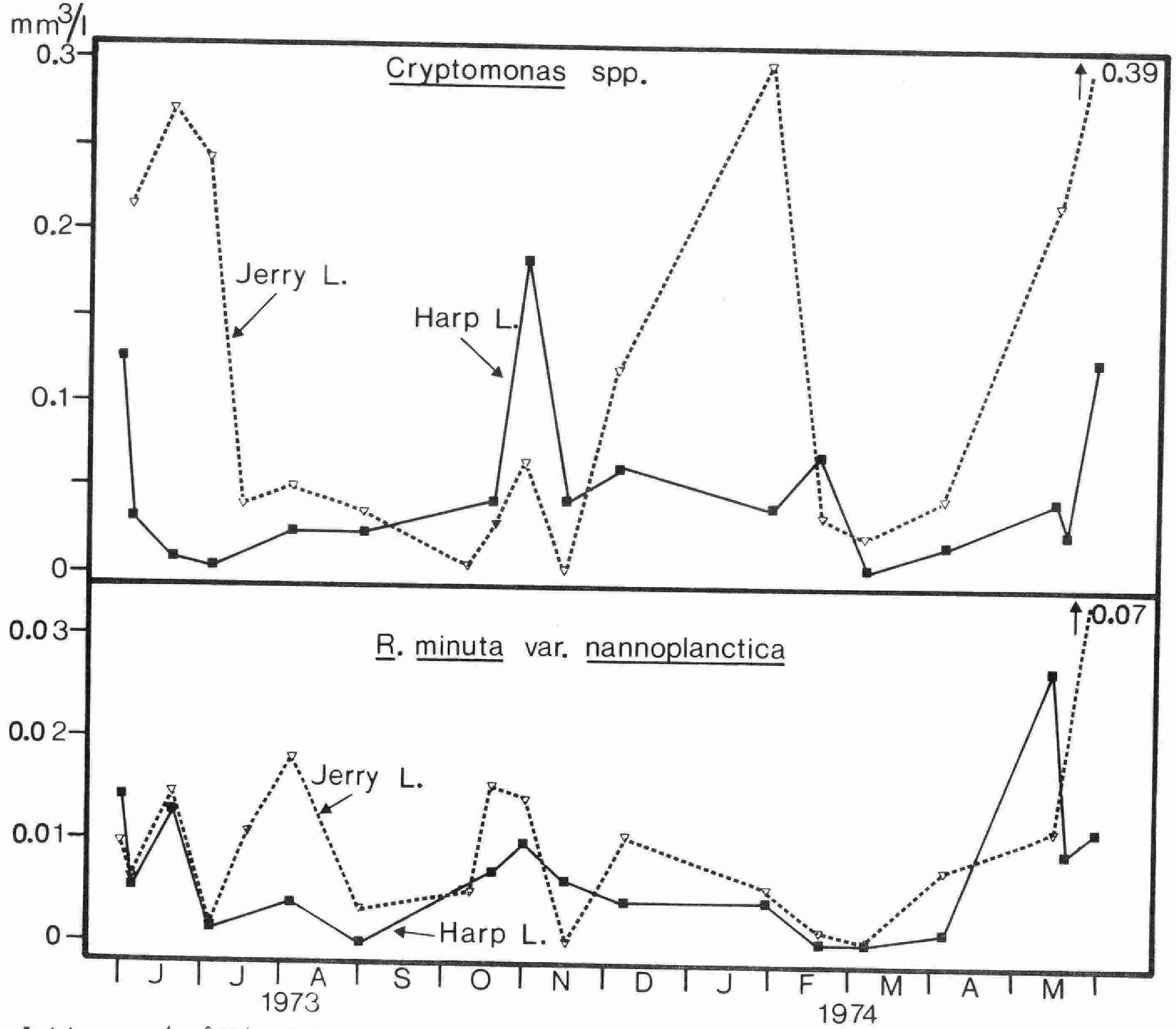

FIG. 26. Seasonal biomass (mm^3/l) of important cryptomonads (Cryptomonas spp. and Rhodomonas minuta var. nannoplanctica) in Harp and Jerry Lakes between May of 1973 and June of 1974.

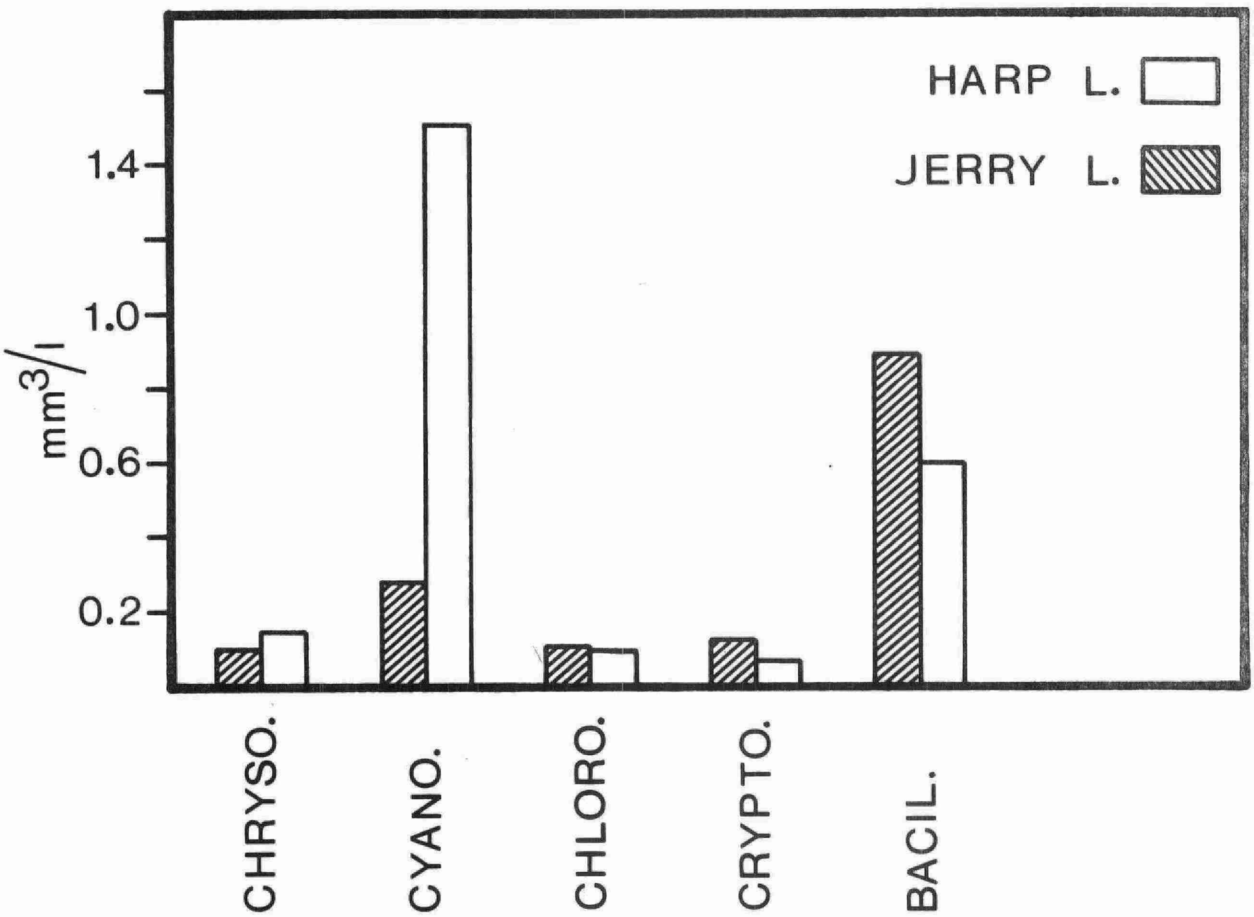

FIG. 27. The dominant algal classes in the phytoplankton as "average" biomass (mm^3/l) calculated from analyses of 17 samples from Harp Lake and 18 samples from Jerry Lake collected over the annual period. (CHRYSO-Chrysophyceae; CYANO-Cyanophyceae; CHLORO-Chlorophyceae; CRYPTO-Cryptophyceae; BACIL - Bacillariophyceae).

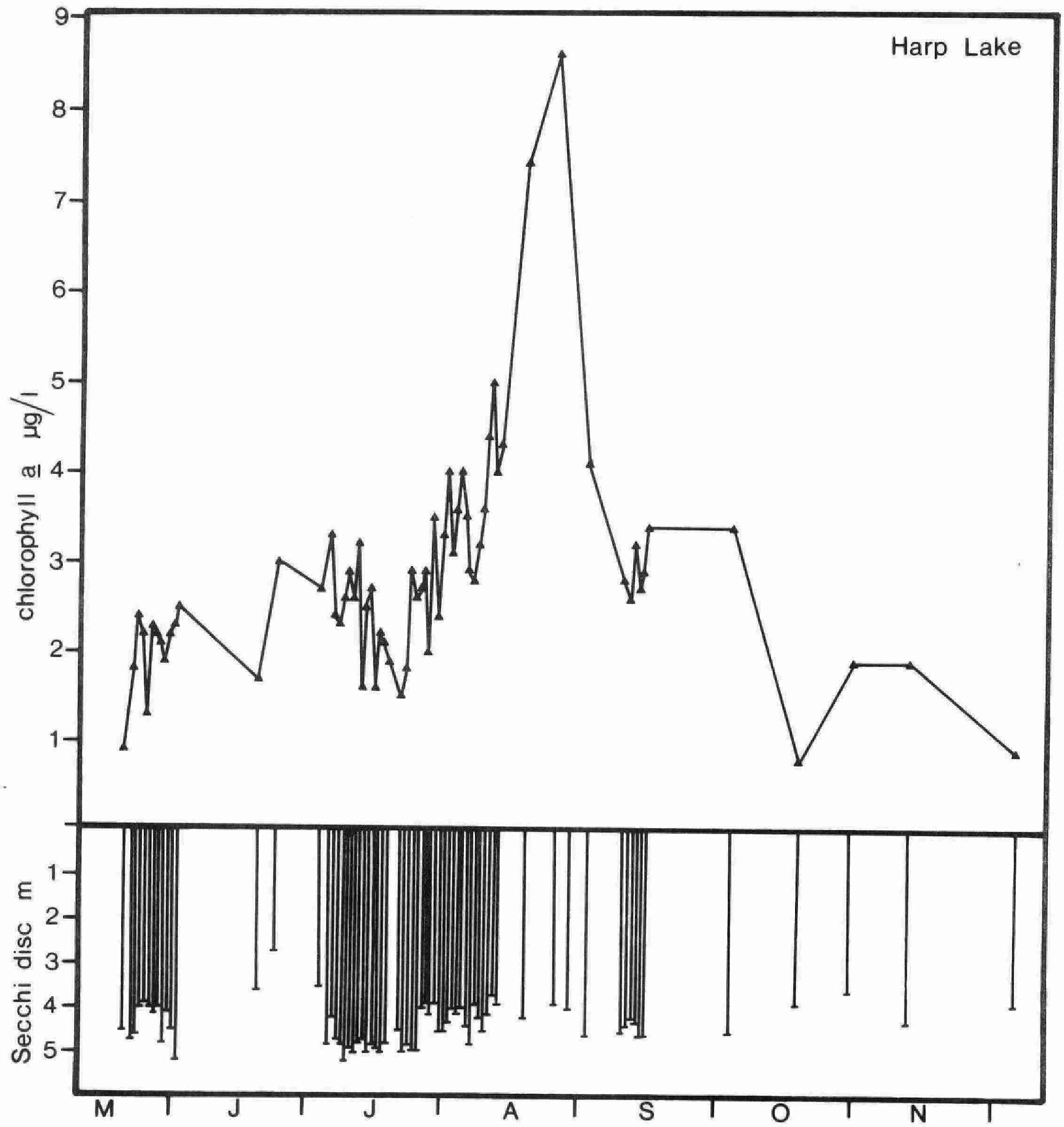

FIG. 28. Seasonal distribution of euphotic zone concentrations of chlorophyll a and Secchi disc visibility in Harp Lake throughout the ice-free period of 1973.

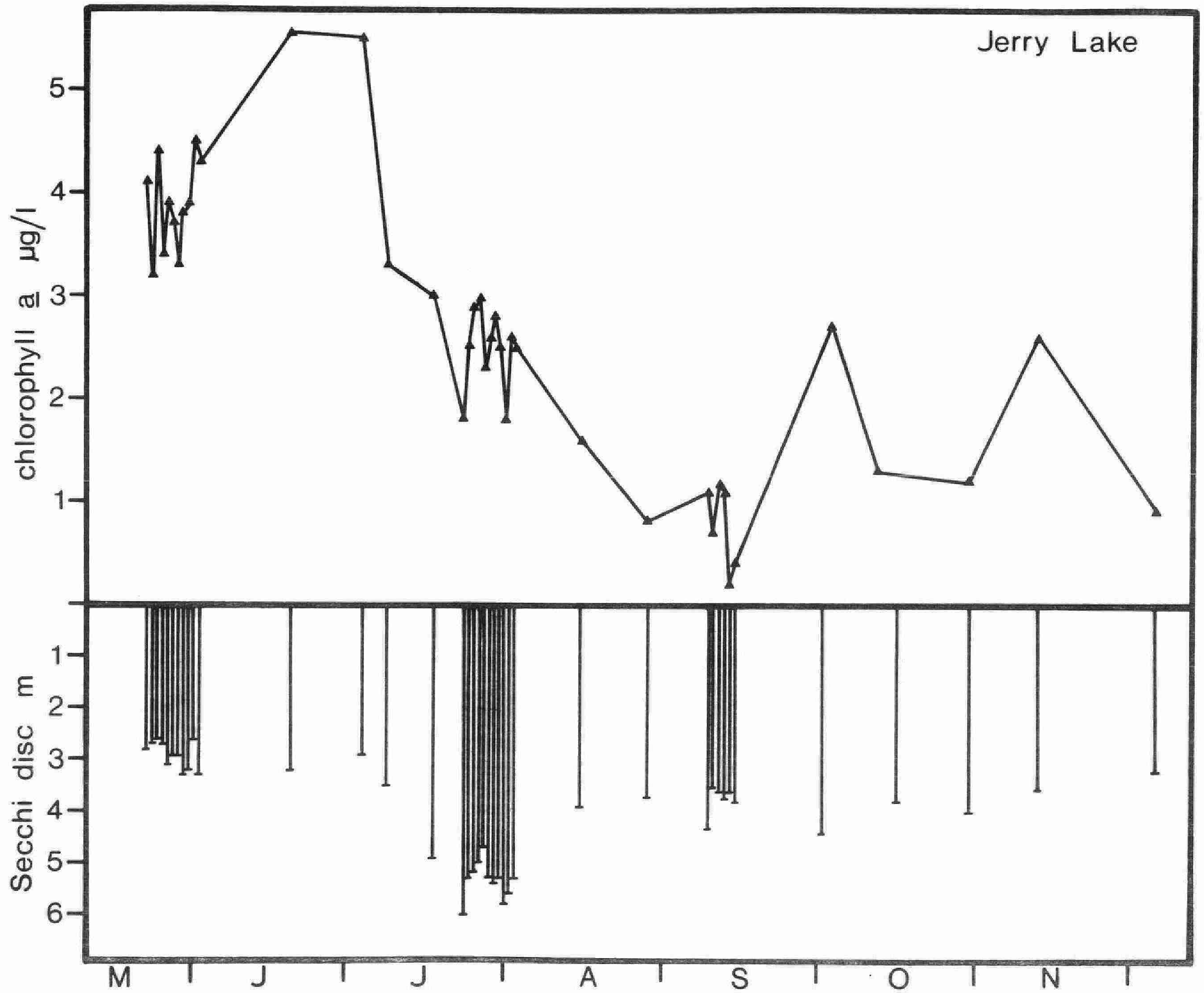

FIG. 29. Seasonal distribution of euphotic zone concentrations of chlorophyll a and Secchi disc visibility in Jerry Lake throughout the ice-free period of 1973.

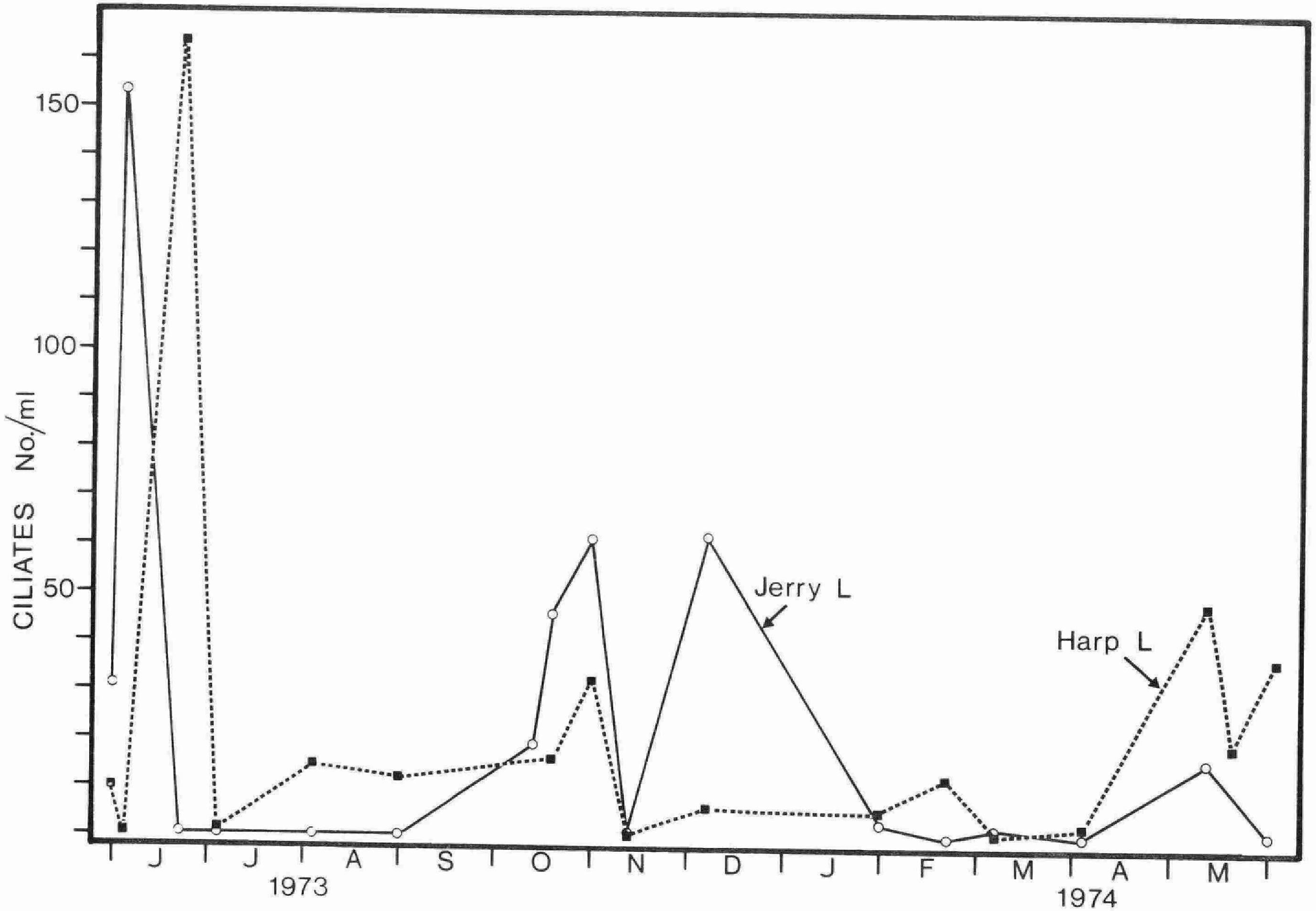

FIG. 30. Seasonal distribution of total ciliates (number/ml) in the euphotic zones of Harp and Jerry Lakes between May of 1973 and June of 1974.

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Appendix 1. Weighted mean total phosphorus concentration (g/m^3), total water volume (m^3) and total P load (g) calculated for each of 39 selected time periods between June 20, 1973 and June 21, 1974 on the Harp Lake inflow.

Time Period	[P], g/m^3	Vol.(m^3)	total P load (g)
20/6 - 4/7	0.068	16,507	1122.5
5/7 - 29/7	0.029	11,540	334.7
30/7 - 8/8	0.080	14,316	1145.3
9/8 - 18/8	0.018	5,113	92.0
19/8 - 28/8	0.025	6,866	171.7
29/8 - 12/9	0.038	3,944	149.9
13/9 - 2/10	0.035	5,405	189.2
3/10 - 10/10	0.025	5,259	131.5
11/10 - 20/10	0.030	15,338	460.1
21/10 - 31/10	0.050	5,843	292.2
1/11 - 7/11	0.022	7,742	170.3
8/11 - 13/11	0.032	3,506	112.2
14/11 - 19/11	0.035	6,428	225.0
20/11 - 28/11	0.050	29,362	1468.1
29/11 - 5/12	0.020	29,946	598.9
6/12 - 11/12	0.022	21,328	469.2
12/12 - 20/12	0.020	9,495	189.9
21/12 - 31/12	0.018	10,810	194.6
1/1 - 30/1	0.018	40,172	723.1
31/1 - 5/2	0.018	9,057	163.0
6/2 - 14/2	0.015	12,271	184.1
15/2 - 24/2	0.015	6,720	100.8
25/2 - 6/3	0.040	13,585	543.4
7/3 - 16/3	0.015	19,721	295.8
17/3 - 25/3	0.015	8,181	122.4
26/3 - 3/4	0.008	8,619	69.0
4/4 - 10/4	0.035	113,505	3972.7
11/4 - 15/4	0.035	90,278	3159.7
16/4 - 17/4	0.020	43,824	876.5
18/4 - 20/4	0.010	40,610	406.1
21/4 - 24/4	0.015	33,599	504.0
25/4 - 30/4	0.015	23,811	357.2
1/5 - 8/5	0.015	14,462	216.9
9/5 - 14/5	0.035	34,037	1191.3
15/5 - 20/5	0.020	29,508	590.2
21/5 - 25/5	0.020	6,428	128.6
26/5 - 30/5	0.020	5,989	119.8
31/5 - 9/6	0.020	8,765	175.3
10/6 - 21/6	0.020	11,102	222.4
		782,992	21639.9

Appendix 2. Weighted mean total phosphorus concentration (g/m^3), total water volume (m^3) and total P load (g) calculated for each of 39 selected time periods between June 20, 1973 and June 21, 1974 on the Harp Lake outflow.

Time Period	[P], g/m^3	Vol.(m^3)	total P load (g)
20/6 - 4/7	0.008	98,312	786.4
5/7 - 29/7	0.015	21,474	322.1
30/7 - 8/8	0.015	90,862	1362.9
9/8 - 18/8	0.020	26,148	522.9
19/8 - 28/8	0.008	30,823	246.6
29/8 - 12/9	0.012	18,114	217.4
13/9 - 2/10	0.015	10,518	157.8
3/10 - 10/10	0.015	13,147	197.2
11/10 - 20/10	0.015	74,501	1117.5
21/10 - 31/10	0.015	37,397	560.9
1/11 - 7/11	0.028	107,369	3006.3
8/11 - 13/11	0.020	47,184	943.6
14/11 - 19/11	0.020	35,205	704.1
20/11 - 28/11	0.010	30,969	309.7
29/11 - 5/12	0.018	141,990	2555.8
6/12 - 11/12	0.010	74,939	749.4
12/12 - 20/12	0.018	73,040	1314.7
21/12 - 31/12	0.015	81,805	1227.1
1/1 - 30/1	0.012	260,461	3125.5
31/1 - 5/2	0.030	73,478	2204.3
6/2 - 14/2	0.010	21,474	214.7
15/2 - 24/2	0.008	34,329	274.6
25/2 - 6/3	0.012	66,028	792.3
7/3 - 16/3	0.010	87,648	876.5
17/3 - 25/3	0.012	53,758	645.1
26/3 - 3/4	0.012	43,970	527.6
4/4 - 10/4	0.012	147,833	1773.9
11/4 - 15/4	0.008	94,173	753.4
16/4 - 17/4	0.015	160,793	2411.9
18/4 - 20/4	0.008	193,280	1546.2
21/4 - 24/4	0.015	144,505	2167.6
25/4 - 30/4	0.018	97,737	1759.3
1/5 - 8/5	0.008	90,132	721.1
9/5 - 14/5	0.028	113,505	3178.1
15/5 - 20/5	0.030	143,597	4307.9
21/5 - 25/5	0.010	52,589	525.9
26/5 - 30/5	0.015	31,115	466.7
31/5 - 9/6	0.022	16,069	353.5
10/6 - 21/6	0.015	35,498	532.5
		2,975,969	46,461.5

Appendix 3. Weighted mean total phosphorus concentration (g/m^3), total water volume (m^3) and total P load (g) calculated for each of 39 selected time periods between June 20, 1973 and June 21, 1974 on the Jerry Lake inflow.

Time Period	[P], g/m^3	Vol.(m^3)	total P load (g)
20/6 - 4/7	0.057	68,644	3912.7
5/7 - 29/7	0.060	52,147	3128.8
30/7 - 8/8	0.065	27,961	1817.4
9/8 - 18/8	0.035	26,143	915.0
19/8 - 28/8	0.065	34,252	2226.4
29/8 - 12/9	0.100	15,379	1537.9
13/9 - 2/10	0.080	24,466	1957.3
3/10 - 10/10	0.070	23,767	1663.7
11/10 - 20/10	0.045	86,120	3875.4
21/10 - 31/10	0.045	35,930	1616.9
1/11 - 7/11	0.035	37,887	1326.0
8/11 - 13/11	0.035	20,412	714.4
14/11 - 19/11	0.025	23,068	576.7
20/11 - 28/11	0.020	95,766	1915.3
29/11 - 5/12	0.018	118,695	2136.5
6/12 - 11/12	0.015	95,067	1426.0
12/12 - 20/12	0.020	42,081	841.6
21/12 - 31/12	0.020	48,092	961.8
1/1 - 30/1	0.030	172,100	5163.0
31/1 - 5/2	0.030	39,145	1174.4
6/2 - 14/2	0.030	46,695	1400.9
15/2 - 24/2	0.030	31,316	939.5
25/2 - 6/3	0.040	56,760	2270.4
7/3 - 16/3	0.055	85,281	4690.5
17/3 - 25/3	0.040	39,145	1565.8
26/3 - 3/4	0.035	31,316	1096.1
4/4 - 10/4	0.038	478,133	18169.1
11/4 - 15/4	0.020	370,064	7401.3
16/4 - 17/4	0.018	157,700	2838.6
18/4 - 20/4	0.018	137,568	2476.2
21/4 - 24/4	0.018	143,859	2589.5
25/4 - 30/4	0.020	77,591	1551.8
1/5 - 8/5	0.023	46,555	1070.8
9/5 - 14/5	0.015	135,891	2038.4
15/5 - 20/5	0.015	97,724	1465.8
21/5 - 25/5	0.025	22,788	569.7
26/5 - 30/5	0.030	24,885	746.6
31/5 - 9/6	0.030	39,145	1145.4
10/6 - 21/6	0.030	42,361	1270.8
		3,151,899	94,184.4

Appendix 4. Weighted mean total phosphorus concentration (g/m^3), total water volume (m^3) and total P load (g) calculated for each of 39 selected time periods between June 20, 1973 and June 21, 1974 on the Jerry Lake outflow.

Time Period	[P], g/m^3	Vol.(m^3)	total P load (g)
20/6 - 4/7	0.030	169,211	5076.3
5/7 - 29/7	0.022	29,250	643.5
30/7 - 8/8	0.010	164,973	1649.7
9/8 - 18/8	0.005	44,831	224.2
19/8 - 28/8	0.010	49,068	490.7
29/8 - 12/9	0.018	30,889	556.0
13/9 - 2/10	0.015	16,128	241.9
3/10 - 10/10	0.012	20,229	242.7
11/10 - 20/10	0.010	110,302	1103.0
21/10 - 31/10	0.010	69,434	694.3
1/11 - 7/11	0.015	167,844	2517.7
8/11 - 13/11	0.012	67,657	811.9
14/11 - 19/11	0.028	64,240	1798.7
20/11 - 28/11	0.020	42,371	847.4
29/11 - 5/12	0.012	191,079	2292.9
6/12 - 11/12	0.010	113,035	1130.4
12/12 - 20/12	0.010	104,971	1049.7
21/12 - 31/12	0.015	119,459	1791.9
1/1 - 30/1	0.012	436,012	5232.1
31/1 - 5/2	0.010	95,676	956.8
6/2 - 14/2	0.010	40,320	403.2
15/2 - 24/2	0.012	91,440	1097.3
25/2 - 6/3	0.010	113,582	1135.8
7/3 - 16/3	0.010	141,055	1410.6
17/3 - 25/3	0.010	89,389	893.9
26/3 - 3/4	0.012	68,204	818.4
4/4 - 10/4	0.010	162,924	1629.2
11/4 - 15/4	0.015	447,493	6716.9
16/4 - 17/4	0.018	209,805	3776.5
18/4 - 20/4	0.020	251,493	5029.9
21/4 - 24/4	0.020	218,963	4379.2
25/4 - 30/4	0.022	205,842	4528.5
1/5 - 8/5	0.025	159,507	3987.7
9/5 - 14/5	0.020	183,562	3671.2
15/5 - 20/5	0.012	205,978	2471.7
21/5 - 25/5	0.020	76,541	1530.8
26/5 - 30/5	0.020	67,110	1342.2
31/5 - 9/6	0.020	27,200	544.0
10/6 - 21/6	0.020	54,672	1093.4
		4,921,739	75,812.2

Appendix 5 - Confidence Limits on J_A

Given the assumptions and inherent errors in measurements and calculations of the P balance for Harp and Jerry Lakes the following exercise is an attempt to assign a "likely range of error" to each major step in the procedure to calculate J_A and to ultimately determine "confidence limits" on the calculated value of J_A = 20.3 kg P/yr. or J_A = 0.28 kg P/cottage·yr.

(1) Hydrologic Budgets

(a) evaporation

Bruce and Weisman (1966) point out that inherent inaccuracies in the development of evaporation maps suggest that 0.65 for Muskoka is accurate to within 10-15% of the true long term average. Errors introduced by the use of their long term evaporation value (0.65 m) are insignificant to the total P balance since a deviation by as much as ± 35% from the 0.65 m value used (allowing an additional 20% for year-to-year variation from the long term average) results in only a ± 4% change in J_A.

ie. Evap. = 0.42m; J_A = 21.2 kg/yr
Evap. = 0.88 m; J_A = 19.5 kg/yr

(b) precipitation

Total precipitation data for the annual study period (June, 1973 to June, 1974) were obtained from Environment Canada from records kept at nearby Huntsville. Data from our own rainfall gauge installed on Harp Lake in May of 1974 and maintained until August 23, 1974, show a 35% difference between Harp Lake rainfall and Huntsville rainfall and undoubtedly illustrates the isolated distribution of summer thunderstorms. Over the whole year, differences in total annual precipitation between the two sites are likely much less. Nevertheless, if a range of ± 35% is ascribed to the precipitation data used in the hydrologic budget calculations, the resultant changes in J_A are only ± 4%.

ie. precipitation = 144 cm; J_A = 21.2 kg/yr
precipitation = 69 cm; J_A = 19.4 kg/yr

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(c) inflow and outflow measurements

It is likely that any errors present, are inherent in all four hydrographs, so that they yield water loads which are either too high or too low. It is not likely that one hydrograph represents a large underestimate of total flow while another represents a large overestimate, since the same methods were used to develop the hydrographs.

As pointed out in the text, the annual runoffs from both the Harp and Jerry total basins were about 30% higher than the long-term average, but total precipitation during the annual period was 16% higher than the long term average. Assuming that at least one-half of the additional precipitation was available for runoff (very likely since the conditions contributing to higher than average precipitation also contribute to lower than average evaporation and evapotranspiration), then about 7-8 cm of the determined runoff from the basins is still unaccounted for (ie. 7-8 cm above the long term average after correction for above average precipitation) and suggests errors in measurement leading to an apparent 10% overestimation of total flow. It is therefore not likely that actual errors in the hydrographs are negative; however, for purposes of this exercise, J_A has been recalculated assuming a range of error in the total inflows and outflows of from -10% to +20%. The resultant change in calculated J_A is:

(i) flows increased by 10%; J_A = 23.3 kg/yr.
(ii) flows decreased by 20%; J_A = 13.6 kg/yr.

(2) Phosphorus Budgets

(a) aeolian inputs

The annual aeolian input of total P of 74 $mg/m^2 \cdot yr$ based on samples from a collection device installed on a rocky shoal of Harp Lake during 1974 and upon snow samples collected from the frozen lake surface (Nicholls and Cox, 1976) is near the highest reported from Ontario, although few detailed measurements have been made. Scheider (1974) measured a total input of 38 mg/m^2 for the 1973 period in nearby Algonquin Park and Dillon (1974) and Gomolka (1975) measured

Appendix 5 - Cont'd....

77 and 37 mg/m^2·yr during 1972 and 1974, respectively in the Haliburton Highlands of Ontario, suggesting that spatial and year-to-year differences in aeolian P inputs in south-central Ontario may be large. Furthermore Schindler et al (1974) have shown that total P supplied from the atmosphere can vary as much as 100% between 2 years at the same location in northwestern Ontario. There may therefore have been considerable error introduced into the Harp and Jerry Lakes P mass balance equations by using the P supply rate determined during 1974 as a component of the 1973 mass balance equations.

Based on the studies published to date on aeolian loading of total P in Ontario, a realistic range might be 30-100 mg P/m^2·yr. When both extremes are substituted into the Harp and Jerry Lakes calculations in place of the 74 mg/m^2·yr (as determined for Harp Lake during 1974), the resulting J_A values are:

(i) J_{PR} = 100 mg P/m^2·yr; J_A = 13.9 kg P/yr

(ii) J_{PR} = 30 mg P/m^2·yr; J_A = 31.4 kg P/yr

The above variations in J_A resulting from the extremes of possible J_{PR} are less likely than the following alteration which corrects a likely error associated with the application of the same aeolian P loading value to both Harp Lake and Jerry Lake.

Nicholls and Cox (1976) suggested that the high measured value (74.5 mg/m^2·day) may have resulted from dust fall. Despite the on-lake installation of their collector, it was felt that dust from the heavily used (and dusty) road circling Harp Lake contributed P to the collector (Dillon's (1974) land based collection site yielding 77 mg/m^2·yr was also near a dusty driveway). Nicholls and Cox (1976) pointed out that further evidence suggesting that road dust might have contributed to high summertime P inputs to Harp Lake could be found in the winter data (when the Harp Lake road was snow covered) and when a measured input of 6.7 mg/m^2 was very similar to Gomolka's (1975) input of 8.4 mg/m^2 during the same time period at a Haliburton site a few km southeast of Harp Lake.

Because the precipitation collector was installed only 50 m offshore, the input of dust to the open lake area could well have been

Appendix 5 - Cont'd....

less than the data indicated. A realistic aeolian input value for Harp Lake might therefore lie somewhere above 37-38 mg/m²/yr (Gomolka's (1975) and Scheider's (1974) data with much less road dust influences) and below the 74.5 mg/m²·yr as measured for Harp Lake's inshore area. If the Jerry Lake input is set at 37 mg/m²·yr as found by Scheider (1974) for the same year a few km east in Algonquin Park, and Harp Lake's input is set at 50 mg/m²·yr, then J_A becomes:

$$\left.\begin{array}{l}\text{Harp } J_{PR} = 50 \text{ mg/m}^2\cdot\text{yr} \\ \text{Jerry } J_{PR} = 37 \text{ mg/m}^2\cdot\text{yr}\end{array}\right) \quad \begin{array}{l} J_A = 19.9 \text{ kg P/yr} \\ \quad \text{or } 0.27 \text{ kg/cottage}\cdot\text{yr}\end{array}$$

Note that this may be the best way to apply the J_{PR} data but it yields a J_A which is only slightly lower than the 20.3 kg/yr derived in the text when the value of J_{PR} = 74.5 mg/m²/yr, as measured for Harp Lake during 1974, was applied to both lakes.

(b) Land drainage inputs

Confidence limits on estimates of P supplied in land drainage are more difficult to establish. For the monitored catchments, part of the error will result from errors in the hydrographs and part from errors in the determination of weighted mean P concentration during the time intervals selected for loading calculations (Appendices 1-4).

Sampling frequency was considered adequate to permit errors in estimates of "real" P concentration resulting from the sampling frequency to "cancel out" over an annual period since high phosphorus concentrations occurring between samplings should be compensated for over the long term by an equal occurrence of "missed" low concentrations. The major errors associated with P input and output calculations from the monitored catchments therefore probably derive from errors in the hydrologic budget (discussed above).

Owing to the large proportion of the total catchment of both Harp and Jerry Lakes comprised of unmonitored area (lacking year-round stream drainage), the method used to extrapolate to total P export from the unmonitored areas would seem critical. Although it is felt that the method used and described in the text offers the best approach, there are two other ways that this might be done.

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(i) One method as used in other studies in Ontario by Johnson and Owen (1971) and Nicholls and MacCrimmon (1975) simply assumes water and phosphorus export values per unit land area of unmonitored catchment to be the same as those from adjacent monitored catchments of similar land use. In the Harp and Jerry Lakes case, this method probably yields an overestimate of P export by overestimating both the P concentration and water export from unmonitored areas, but if applied, the J_A becomes:

J_A = 9.7 kg/yr, or 0.13 kg/cottage·yr

(ii) Dillon (1974) chose to apply the areal water export as measured in catchments served by streams to unstreamed catchments and multiplied by a concentration of 5.2 mg P/m^3 as assumed for groundwater.

The assumption inherent here cannot likely be applied to Harp Lake since a marked increase in P concentration of the inflow was observed during a peak in the hydrograph and undoubtedly indicates surface drainage of snow melt from within the catchment of much higher total P concentration than 5.2 mg/m^3 (ie. weighted mean total P concentration increased from 8 mg/m^3 during late March and early April to 35 mg/m^3 during the period April 4 to April 15 accompanying maximum flows (see Fig. 14 and Appendix 1). Nevertheless, if this method is used,

J_A = 20.5 kg/yr or 0.28 kg/cottage·yr and is essentially the same as that obtained by the preferred method, outlined in the text.

(iii) Another possible source of error in the P budget could relate to errors in the estimated sizes of the catchments. Errors in the estimated sizes of the monitored catchments have no effect on the J_A; however, errors in the unmonitored catchments

Appendix 5 - Cont'd....

are significant to calculations of J_A. Errors of ± 20% are considered possible for both Harp and Jerry Lakes unmonitored areas, so that Harp Lake's unmonitored catchment area may be as large as 4.13 km^2 or as small as 2.75 km^2 and Jerry Lake's unmonitored catchment may be as large as 4.43 km^2 or as small as 2.95 km^2.

If catchment areas for both lakes have been either overestimated or underestimated by 20%, little change in J_A results. In either case,

J_A = 21.5 kg/yr or 0.29 kg/cottage·yr.

However, if Jerry Lake's unmonitored catchment area has been overestimated by 20% and Harp Lake's catchment, underestimated by 20%, then,

J_A = 9.8 kg/yr or 0.13 kg/cottage·yr.

Similarly, if Jerry Lake's unmonitored catchment area is increased by 20%, and Harp Lake's catchment, decreased by 20%,

J_A = 33.2 kg/yr or 0.45 kg/cottage·yr.

(3) Sedimentation

(i) It is important to stress at the outset that the validity of the approach taken lies in the assumption that the S_{gross}-to-S_{net} ratio is the same in both lakes. If the ratios differ by only 10%, a 50% change in J_A results.

But, as pointed out in the text, there do not appear to be any reasons to expect the ratios to be different since the factors contributing to higher S_{gross} on one lake should also contribute to proportionately higher S_{net} in that lake.

It is also important to stress that errors in the measurement of S_{gross} (sedimentation traps) are not important to the final calculation of J_A as long as the same errors are inherent in measurements on both lakes. For example, if the gross sedimentation rates have been overestimated by 100%, J_A changes as follows:

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Harp Lake: S_{gross} = 486 kg P/yr

Jerry Lake: S_{gross} = 537 kg P/yr; $\frac{S_{gross}}{S_{net}} = 5.4$

and J_A = 20.7 kg/yr or 0.28 kg/cottage·yr.

(ii) Another method of extrapolating mid-lake sedimentation rates to the whole lake basin is according to Fuhs (1973) and is given in the text. If the S_{gross} values derived from Fuhs' method are used in the calculations,

J_A = 14.5 kg/yr or 0.20 kg/cottage·yr.

Conclusions

It would appear that the best estimate of J_A (20.3 kg/yr can range between 9.7 kg/yr and 33.2 kg/yr when single steps in the calculation of J_A are altered to account for possible errors in measurement or a change in methods of extrapolation from measured components to unmeasured components.

The changes in J_A are not additive given more than one of the alterations discussed above. By combining 1 (c-ii), 2 (a-i), 2 (b-iii) and 3 (ii), above,

J_A = -12.5 kg/yr or -0.17 kg/cottage·yr.

Similarly, when alterations 1 (c-i), 2 (a-ii) and 2 (b-iii) are combined, the maximum cottage input can be shown to be:

J_A = 47.3 kg/yr or 0.65 kg/cottage·yr.

It should be remembered however, that each of the alterations discussed above represents an extreme of a range of possible errors or methods of extrapolation and it is more likely that the true J_A lies closer to the "best value" of 20.3 kg/yr or 0.28 kg/cottage·yr than to the extremes of -0.17 and +0.65 kg/cottage·yr derived from the combination of possible errors in the method.

In fact, the true J_A for Harp Lake probably lies somewhere between 0 and 0.28 kg/cottage·yr since it can be shown that with J_A = 0.28 kg/cottage·yr, the springtime concentration of phosphorus in Harp Lake should be 14 μg/l according to Dillon and Rigler's (1974) equation: $[P] = \frac{L(1-R)}{\bar{z}\rho}$.

The measured[1] concentration in Harp Lake was 13 μg/l. If J_A is set at 0 and 0.65 kg/cottage·yr, the predicted springtime phosphorus concentrations are 12 and 18 μg P/l, respectively.

[1]*FOOTNOTE: Two euphotic zone samples collected on Harp Lake on May 2 and May 13 showed total P concentration in the lake during spring overturn to be 7 and 17 μg/l. Over a similar range, late winter and springtime outflow samples showed a weighted mean total P concentration of 13 μg/l (28 analyses from mid-February to mid-May) and is considered a better measure of [P] for use in Dillon and Rigler's (1974) equation:* $[P] = \frac{L\,(1-R)}{\bar{z}\,\rho}$.